Spectroscopic Study of the Vela-Shrapnel

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Abstract

Several shrapnels have been detected in the vicinity of Vela SNR by the ROSAT all-sky survey. We present here the spectral properties of shrapnel ‘A’ observed with the ASCA satellite. A prominent Si-K emission line with relatively weak emission lines from other elements have been detected, revealing that the relative abundance of Si is a few ten-times higher than those of other elements. Combining with the ROSAT PSPC results, we obtained the electron temperature, $kT_e$, to be $0.33 \pm 0.01$ keV. The total mass of shrapnel ‘A’ is estimated to be $\sim 0.01 M_\odot$. If it is an ejecta of a supernova explosion, the interstellar matter (ISM) would be swept up in the leading edge while the ejecta material would be peeled off in the trailing edge, which should be confirmed by future observations.

Key words: ISM: individual (Vela supernova remnant) — ISM: supernova remnants — ISM: abundances — X-Rays: ISM
1. Introduction

The nucleosynthesis process inside a star generates high-Z elements, and supernova explosions spew them out into interstellar space. Young supernova remnants (SNRs), like Cassiopeia-A (Holt et al. 1994), Tycho (Hwang, Gotthelf 1997) and Kepler’s SNR (Kinugasa, Tsunemi 1999), show clear X-ray emission lines from various heavy elements, indicating their overabundance. These emission lines are mainly produced by ejecta, enriched by heavy elements.

Middle-aged SNRs, like the Cygnus Loop, show X-ray emission lines produced by swept-up interstellar matter (ISM). The metal abundances in the shell region are rather low (Miyata et al. 1994). Since the swept-up matter is much more massive than the ejecta, the apparent abundances in these systems represent the ISM composition. The Cygnus Loop has a shell structure, showing that the major constituents are swept-up matter in the shell region. Whereas, Miyata et al. (1998) detected a substantial amount of heavy elements in the center region of the Loop. The X-ray spectra show an overabundance by a factor of several or more compared with the cosmic values. They concluded that the heavy elements were left in the core of the Cygnus Loop, probably a fossil of the ejecta. Therefore, matter enriched by heavy elements is left, and still exists, even in the middle-aged SNR.

The kinds of heavy elements produced in a supernova depend on the type of supernova explosion. High-Z elements, like A, Ca and Fe, are generated dominantly in a Type-I supernova (Nomoto et al. 1984) while low-Z elements, like O, Ne, Mg and Si, are generated in a Type-II supernova (Thielemann et al. 1996). Comparing the relative metal abundances with model calculations, Miyata et al. (1998) concluded that the Cygnus Loop originated from a Type-II supernova, suggesting a massive star as the progenitor.

Aschenbach et al. (1995, called AET hereafter) observed the entire Vela SNR, which is also a typical middle-aged one, in the ROSAT all-sky survey. The SNR clearly shows a circular structure with a diameter of 47.5, probably consisting of swept-up ISM. Furthermore, they detected ‘shrapnels’, boomerang structures (from ‘A’ to ‘F’), outside of the main shell. The opening angles of the shrapnels suggest supersonic motion in a tenuous matter. These structures agree well with the assumption that they originated in the center of the main shell, which is very close to the Vela pulsar, 0833–45.

If the shrapnels are fossil material of the supernova explosion, we expect that their spectra would
show a metal-rich composition regardless of the type of supernova. There have been several fragments discovered so far (AET). Among them, fragment ‘A’ has been selected for an ASCA observation. This fragment is neither the brightest nor the largest one. Since its apparent size is $4' \times 7'$, it is suitable for a study with the ASCA SIS (Yamashita et al. 1997), which has a field of view (FOV) of $11'$ square for one CCD chip. AET found that there was a relatively hot gas surrounding Vela SNR. Therefore, the ambient condition around Vela SNR might be different from that of the standard SNR. From these viewpoints, we selected fragment ‘A’ in order to observe the source and the background simultaneously.

The GIS instrument (Ohashi et al. 1996) has a large circular FOV with a diameter of $\sim 50'$ with a higher detection efficiency at higher energies, while it has a less efficiency in a lower energy range with poorer energy resolution than the SIS. Therefore, the GIS is not very suitable to determine the background spectrum for the SIS data. This paper describes the results of a combined analysis of the ASCA and ROSAT data.

2. Observation and Results with ASCA

We performed observations of fragment ‘A’ during 1994 May 31 – June 3, with the four-CCD mode at a high bit rate and with the two-CCD mode in medium bit rate, resulting the effective exposure time of 91 ks. Figure 1 shows the X-ray surface brightness map obtained with two GIS sensors in a logarithmic gray scale, where the SIS FOV is shown by squares. There are two sources in the FOV: the left one is a serendipitous source (CU Vel, a point source) and the right one is shrapnel ‘A’ (an extended source).

The SIS, functioning in four/two CCD modes, is pointed at $\alpha = 08^h57^m13^s, \delta = -41^\circ53'22''$ (2000). This enables us to cover the major part of fragment ‘A’ in one CCD chip, while other chips cover both the tail part and the surrounding region. The observed region is divided into two parts. One is a circular region with a radius of $6'$ centered on fragment ‘A’. The other is its surrounding region excluding the serendipitous source (CU Vel) in the east of fragment ‘A’. This configuration is shown in figure 1. The spectrum outside the circular region is found to be statistically consistent with the standard background, accumulated in the Lynx field and in the NEP field (Gendreau et al. 1995). Therefore, we subtracted the standard background spectrum from the present data to obtain better statistics. The count rate inside
the circular region is $2.4 \times 10^{-2} \text{ c s}^{-1}$ /SIS and $1.6 \times 10^{-2} \text{ c s}^{-1}$ /GIS, respectively.

We further divided the circular region into two parts: the northeast half circle (leading part) and the southwest half circle (trailing part). Since spectral fits show no significant difference between the two spectra in these regions, the spectral data in the circular region were combined and treated together.

Figure 2 shows the SIS spectrum with crosses. The spectrum is fairly smooth below 1 keV, whereas a strong emission line is seen around 1.8 keV, which is considered to be the Si-K (Si XIII) emission line. There are two weak structures around 0.8 and 0.9 keV corresponding to the energies of Fe-L (Fe XVII) and Ne-K (Ne IX) emission lines, respectively. Various spectral models were applied to examine the SIS data, as described below. In the spectral fits below, the interstellar absorption, $N_H$, was fixed at $3.5 \times 10^{20}$ H atoms cm$^{-2}$, as determined by the ROSAT PSPC (AET). This level of $N_H$ is almost undetectable with the SIS.

2.1. CIE Model with Cosmic Abundance

The collisional ionization equilibrium (CIE) model with a single-$kT_e$ (Raymond, Smith 1977) was applied at first. A model with cosmic abundance (Anders, Grevesse 1989) gave an unacceptable fit, as shown in table 1. We then employed a model with two different $kT_e$ with cosmic abundance, since AET reported that the PSPC spectrum could be well fitted with this model. The results are described in table 1. We found that the model yielded statistically unacceptable fits.

2.2. CIE Model with Variable Abundance

Next, we applied a single-$kT_e$ CIE model with variable abundances of elements. In this fitting, the abundance of He was fixed to the cosmic value, those of C and N are anchored to that of O, and those of O, Ne, Mg, Si, Fe, and Ni were left as free parameters. The best-fit model and parameters are shown in figure 2 and in table 1. The major discrepancy between the model and the data in this fit lies in the energy range of 1.1 – 1.2 keV where the data are dominated by Fe-L line blends.

Then, we added an extra component with different $kT_e$ and cosmic abundances of elements. This model gave us a moderately good fit in the $\chi^2$ statistics. However, a major deviation of the model still exists in the energy range between 1.1–1.2 keV, indicating that the extra component is unable to fill up
the gap between the model and the data. If we leave the abundances for both components to be free, no meaningful parameters are obtained, because the model has too many free parameters to adjust.

Through a fit with two temperature components, we found that the spectrum in the energy range above 1.2 keV could be well fitted with the $kT_e \sim 0.8$ keV component, while the data below $\sim 1$ keV could be well reproduced with the $kT_e \sim 0.3$ keV component. The obtained values of $kT_e$ for these two components are consistent with the PSPC results (AET). The high-$kT_e$ component is mainly responsible for both the continuum emission and the Si emission line. The intensity ratio between the continuum and the Si line constrains the value of $kT_e$ when the cosmic abundance is assumed. If we do not fix the metal abundance, the variation of $kT_e$ would be inversely proportional to the relative abundance of Si compared with those of other heavy elements.

2.3. *Fe-L Problem*

We applied various models, as described in the previous section, but obtained no acceptable fits in the $\chi^2$ statistics. A large discrepancy in the energy range of 1.1 – 1.2 keV was found for all models, particularly not in the GIS, but in the SIS data. The better energy resolution seems to result in a larger deviation of the model. This suggests that emission lines are involved in this part of the spectrum. Based on these results, we suspect that the poor spectral fits result from improper knowledge of the Fe-L lines ($n = 3 \to 2$), which mainly contribute to the spectrum in this energy range. A similar discrepancy was noticed in the SNR spectrum (Miyata et al. 1998). Since we need a multi-$kT_e$ model to reproduce the spectrum of the SNR, the disagreement between models and data may be partly due to too simple modeling of the spectrum. A similar problem has also been reported in an analysis of the Centaurus cluster (Fabian et al. 1994). Liedahl et al. (1995) recalculated the emissivity of the Fe-L line blend and found some deviation from the previous model. They claimed that the deviation was mainly caused by a problem in atomic data. Liedahl’s calculation indicated that the emissivity of the $n = 3 \to 2$ line became 30% higher than that used in the current plasma models, which could qualitatively solve our problem in the spectral fits. We employed the new model for thin thermal emission (called VMEKAL in the XSPEC) and fit the data again (Mewe et al. 1985). However, the new model did not significantly improve the fit.
The problem still seems to remain in the current models (Brickhouse et al. 1995). Since we could not access the revised atomic data, which would solve the discrepancy, we decided to mask the energy range of 1.1 – 1.2 keV in the SIS spectral analysis, while no mask was applied for the GIS data.

2.4. Spectral Fits — Ignoring Fe-L

We applied single-$kT_e$ and two-$kT_e$ CIE models with the cosmic abundance, but could not obtain a reasonable fit to the data. Therefore, we fitted the SIS spectrum with a single-$kT_e$ CIE model with variable abundance excluding the data in the energy range of 1.1 – 1.2 keV. In this fit, the $N_H$ value was fixed to that obtained by the ROSAT PSPC (AET). The best-fit curve and parameters are shown in figure 3 and in table 1. As shown in the bottom panel of figure 3, the residuals show random scatter, except for the energy range of 1.1 – 1.2 keV. This feature indicates that the model can be made statistically acceptable by introducing certain systematic errors. It should be noted that O is strongly depleted in our fit. The $N_H$ value employed here is fairly low, and the SIS should be able to detect the O-line feature easily in the spectrum. Since the $N_H$ value strongly correlates with the O abundance in the spectral fit, the above conclusion sensitively depends on the $N_H$ value derived from the PSPC data. If the O abundance was raised to the cosmic level, a substantially higher value of $N_H$ would be required in order to reproduce the SIS spectrum. This is obviously inconsistent with the PSPC result.

The abundance values given in table 1 are based on the assumption that He abundance is cosmic and C and N have equal abundance to O. Even though we have no effective way to confirm how adequate this assumption is, we can claim that abundance ratio between O and Si is much smaller than the cosmic value. If the abundances of He, C, N, and O were assumed to be cosmic, Si would have to be about several hundred times more abundant than the cosmic level (Tsunemi, Miyata 1997).

3. Combined Analysis with the ROSAT Data

We obtained a consistent spectral fit between the SIS data and the GIS data by ignoring the energy range of 1.1 – 1.2 keV. Since both instruments are insensitive to the energy range below 0.4 keV, we have to fix the $N_H$ value to the previously reported one (AET). PSPC is sensitive down to 0.1 keV.
(Pfeffermann et al. 1987), while its energy resolution is not sufficient to determine the metal abundances. We checked the model by incorporating the PSPC data, which were obtained with a pointing observation on 1992 May 31 – June 1. Data screening was performed with esas developed by Snowden (Snowden et al. 1994; Snowden 1995). The net exposure time was $\sim 8$ ks.

We performed model fitting using all three data sets: the SIS, the GIS, and the PSPC. The model spectrum used is the CIE model described before. The best-fit curve and parameters are shown in figure 4 and in table 1. The $N_H$ value obtained from our analysis is consistent with that obtained by the PSPC alone (AET). The metal abundances obtained from the three sets of data are, however, a few-times larger than those obtained with the SIS data only. We notice that the relative abundances are similar to the previous results on the SIS data only. Since the PSPC is sensitive to the low-energy region where the emission lines from C and N play a dominant role, it might be inappropriate to assume that the abundances of C and N are equal to that of O. However, we could not practically obtain meaningful values of the C and N abundances when we left them as free parameters. Based on these spectral fits, we can conclude that the abundance ratio between O and Si is $8^{+6}_{-5} \times 10^{-2}$ times the cosmic value, much smaller than the cosmic abundance ratio.

It is not surprising that the CIE model does not give us a satisfactory fit. We then employed a non-equilibrium ionization (NEI) model and fitted all three data sets, simultaneously. The only NEI code practically available at present is the Masai model (Masai 1984; Masai 1994) which does not employ the revised atomic code (Liedahl et al. 1995). The best-fit curve and parameters are also shown in figure 5 and in table 1. The best-fit ionization timescale, $\log \tau$, is $11.4 \pm 0.2$. This indicates that the plasma condition is relatively close to CIE, which is approximately achieved at $\log \tau \sim 12$. Therefore, the spectrum should be consistently expressed with the CIE model. The absolute abundance predicted by the spectral fits depends on the employed model, and is strongly correlated with other parameters, whereas we find that the abundance ratio between O and Si, $6^{+4}_{-3} \times 10^{-2}$ for the NEI model, is relatively robust.
4. Discussion

We have observed shrapnel ‘A’ with ASCA. The high-energy resolution of the detector reveals relatively strong emission lines around 1.8 keV corresponding to the Si-K emission lines. The other interesting spectral feature is that almost no emission lines are seen around 0.6 – 0.7 keV, the energy band for the O-K lines. These results suggest high Si and low O abundances. In the spectral analysis, we assumed the abundance ratio among C, N, and O to be equal to the cosmic value, while the absolute abundance value was left as a free parameter.

Low abundances of C, N, and O are, thus, resulted due to a lack of O emission lines. Consequently H and He contributions dominate the spectrum, further reducing the abundances of high-Z elements. Therefore, the absolute abundance values given in table 1 may not be correct. The absolute abundance of each element should be examined by resolving all of the emission lines with high-resolution instruments in the future. However, the relative abundance derived here should be more reliable, and it clearly shows that Si is extremely overabundant compared with O. This feature strongly supports the idea that shrapnel ‘A’ mainly contains supernova ejecta rather than the ISM.

Strom et al. (1995) detected radio emission from the leading edge of shrapnel ‘A’, showing shock heating of the ambient medium by the supersonic motion. Shrapnel ‘A’ is about 5°2 away from the center of the main shell, indicating the actual distance \( d \) to be \( 45.5 \times (D/500 \text{ pc})/\sin \theta \text{ pc} \), where \( \theta \) is the angle between the line of sight and the moving direction of shrapnel ‘A’. The mean velocity, \( v_{\text{mean}} \), is \( 4400 (d/45.5 \text{ pc})(t/10000 \text{ yr})^{-1} \text{ km s}^{-1} \), where \( t \) is the age of the SNR, whereas the current velocity, \( v_{\text{current}} \), is \( 200 \text{ km s}^{-1}(kT_e/0.3 \text{ keV})^{0.5} \). This indicates an order-of-magnitude deceleration.

AET reported the detection of a tenuous plasma with a high temperature in the vicinity of Vela SNR. Based on their PSPC result and the opening angle of the cone, the temperature of shrapnel ‘A’ is expected to be about 0.6 keV, which is two-times higher than that which we obtained here. Due to the difference in the energy resolving power between the ASCA SIS and the ROSAT PSPC, we believe that the actual temperature of shrapnel ‘A’ is around 0.3 keV.

If shrapnel ‘A’ is actually a moving ejecta, it would be slowed down by the Ram pressure. The deceleration is estimated to be \( \frac{dv}{dt} = -\left( \frac{\rho}{\rho_0} \right) \left( \frac{v^2}{l} \right) f \), where \( v, \rho_0, l \), and \( f \) are the velocity, the density,
the length of shrapnel, and its filling factor, respectively, while \( \rho \) is the density of the ambient matter. If the shrapnel was injected during the supernova explosion with an initial velocity of \( \sim 10^4 \) km s\(^{-1}\) (Shigeyama et al. 1994), it should have lost almost all kinetic energy, since \( v_{\text{current}} \) is on the order of \( \sim 10^2 \) km s\(^{-1}\). If the shrapnel has been keeping its shape since the explosion, we can approximate \( \rho d \sim \rho_0 l f \). We can estimate \( \rho_0 \) to be \( 2 \times 10^{-2} \) H atoms cm\(^{-3}\) based on the data in table 1 assuming that \( f \) is unity. This supports the picture that the explosion of Vela SN occurred in a bubble of hot tenuous gas. The temperature of the ambient medium is as high as that expected for an old SNR, while the pressure is very close to the ISM level due to its low density.

The total mass of shrapnel ‘A’ is estimated to be \( \sim 10^{-2} f^{0.5} M_\odot \). Because of the relatively high abundance of Si, it is likely that the shrapnel originated from the inner part of the progenitor star. If it is the case, the amount of H must be relatively small, resulting in a decrease of the estimated mass. A two-dimensional hydrodynamic calculation of a supernova explosion reveals the formation of a Rayleigh–Taylor instability and a convective instability (Burrows et al. 1992). Young et al. (1997) proposed a double-supernova model for Vela SNR: one exploded about 150000 years ago, forming a tenuous high-temperature plasma, and the other exploded some 10000 years ago. They reported that the collision of the secondary supernova shock with the primary ejecta could produce fragmented ejecta with various abundance anomalies.

Assuming that shrapnel ‘A’ is really a debris of the explosion of the progenitor star, the leading part should have been contaminated by the ISM and the trailing part should have lost some of the original material by peeling. The top part would consist of swept-up matter, while the bottom part would show the raw composition of the shrapnel. The swept-up matter would be formed by two parts: the inner part is the swept-up matter of the supernova ejecta while the outer part is the swept-up ISM surrounding the SNR. Therefore, we expect stratification of three layers in the top part: the ISM, the ejecta and the original matter. The thickness of each layer would have an angular scale of around 30", which is far beyond the imaging capability of ASCA. Such further evidence of the debris would be obtained by observing the shrapnel with high spatial resolution.
5. Conclusion

We have observed shrapnel ‘A’ in Vela SNR with ASCA. The X-ray spectrum shows a prominent Si-K emission line, and a spectral analysis indicates an abnormal metal abundance. The abundance ratio between O and Si is only $4^{+3}_{-2} \times 10^{-2}$ times the cosmic value, implying that a relative abundance of Si is a few tens of times higher than that of O. Combining with the ROSAT PSPC data, we still have a relative abundance anomaly between Si and other elements. We should note that the relative abundances of heavy elements are consistent to be the cosmic values, except for Si.

The mass of shrapnel ‘A’ is $\sim 10^{-2} f^{0.5} M_\odot$, which can be a debris of the progenitor star of the supernova explosion. The current velocity is about $200 \text{ km s}^{-1}$, while its initial velocity is expected to be on the order of $10^4 \text{ km s}^{-1}$. It is still a question how the shrapnel was formed and survived through passage of the SNR shell. A spatially resolved spectroscopic study in the future should confirm its nature, whether or not it really comes from the progenitor star.

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Fig. 1. X-ray intensity map obtained with the GIS shown in a logarithmic gray scale. The FOV of the SIS is superposed with squares, while the circle shows the region from which we extracted the spectrum. Two sources are seen: the left one is a serendipitous source (CU Vel, a point source) and the right one is shrapnel ‘A’ (an extended source).

Fig. 2. X-ray spectrum obtained with the SIS. The crosses show the data points with ± 1σ errors. The solid line shows the best-fit curve of the single-$kT_e$ CIE model with variable abundance and the lower panel shows the residuals of the fit.

Fig. 3. Same as figure 2, but ignored between 1.1 – 1.2 keV (shown as dotted crosses in lower panel).

Fig. 4. Combine fitting for the SIS, the GIS, and the PSPC spectra using the CIE model.

Fig. 5. Same as figure 4, but using the NEI model.
### Table 1. Fitting Results

| Model                     | Red. $\chi^2$ (d.o.f.) | kTe [keV] | C,N,O  | Ne  | Mg  | Si   | Fe   | EM  |
|---------------------------|-------------------------|-----------|--------|-----|-----|------|------|-----|
| 1-kTe cosmic              | 13 (83)                 | 0.40      | $1^a$  | $1^a$| $1^a$| $1^a$| 1    |
| 2-kTe cosmic              | 2.7 (81)                | 0.21/0.78 | $1^a$  | $1^a$| $1^a$| $1^a$| 1/0.0 | 0.10/8.4×|
| 1-kTe variable            | 1.9 (77)                | 0.32      | $2\times10^{-2}$ | $8\times10^{-2}$ | $2\times10^{-2}$ | 0.5 | $2\times10^{-2}$ | 3.2 |
| 1-kTe with variable model |                         |           |        |     |     |      |      |     |
| SIS                       | 1.3 (72)                | 0.31 ± 0.02 | $3_{\pm2}^{+3} \times10^{-2}$ | $3_{\pm0.05}^{+0.09}$ | $0.11_{-0.06}^{+0.1}$ | $1.0_{-0.3}^{+0.5}$ | $4_{\pm2}^{+2} \times10^{-2}$ | $1_{\pm0}^{+0}$ |
| GIS                       | 1.4 (108)               | 0.28$^{+0.01}_{-0.03}$ |        |     |     |      |      |     |
| PSPC                      | 2.0 (16)                | 0.26$^{+0.02}_{-0.01}$ |        |     |     |      |      |     |
| Combine                   | 1.5 (199)               | 0.30 ± 0.02 | $5_{\pm2}^{+4} \times10^{-2}$ | 0.2 ± 0.1 | 0.2 ± 0.1 | $1.5_{-0.5}^{+0.8}$ | $7_{\pm2}^{+4} \times10^{-2}$ | 1.0 ± 0.0 |

**Note** — The quoted errors are at 90 % confidence level.

- **a** Fixed to unity.
- **b** EM (emission measure) is defined as $(\frac{D}{500})^2 n_e n_H V$ [pc$^3$ cm$^{-6}$]. Here, $D$ is distance [pc], $V$ is volume [pc$^3$], $n_e$ is electron number density [cm$^{-3}$], and $n_H$ is hydrogen number density [cm$^{-3}$].
- **c** Assuming the spherical symmetry and uniformity of the source and radius to be $2.5' \approx 0.36$ pc.
- **d** Ignore 1.1 – 1.2 keV range when fitting.
- **e** Obtained $N_H$ was $(5 \pm 1) \times10^{20}$ H atoms cm$^{-2}$.
- **f** Obtained $N_H$ was $(3.5 \pm 0.8) \times10^{20}$ H atoms cm$^{-2}$.
$x10^{-3} \text{c/s/arcmin}^2$
