RX J0852.0−4622: ANOTHER NONTHERMAL SHELL-TYPE SUPERNOVA REMNANT (G266.2−1.2)

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ABSTRACT

The newly discovered supernova remnant G266.2−1.2 (RX J0852.0−4622), along the line of sight to the Vela supernova remnant (SNR), was observed with ASCA for 120 ks. We find that the X-ray spectrum is featureless and well described by a power law, extending to three of the class of shell-type SNRs dominated by nonthermal X-ray emission. Like G347.3−0.5, this low-latitude remnant displays discrete regions of enhanced emission along the rim as well as faint nonthermal emission from the interior. We derive limits on the thermal content of the remnant emission, although the presence of the Vela SNR compromises our ability to seriously constrain a low-temperature component. Limits placed on the amount of Sc-K emission are compared with the expected flux based on the reported 44Ti emission from G266.2−1.2. We also report on an unresolved X-ray source surrounded by diffuse emission near the center of the remnant. The properties of the source are not well determined but appear consistent with the interpretation that the source is a neutron star surrounded by a synchrotron nebula. Alternatively, the source may be associated with one of two stars located within the positional error box, but this appears somewhat unlikely.

Subject headings: ISM: individual (G266.2−1.2) — radiation mechanisms: nonthermal — supernova remnants — X-rays: ISM

1. INTRODUCTION

Young supernova remnants (SNRs) are believed to be the prime accelerators of cosmic rays, at least up to the “knee” of the cosmic ray spectrum at energies of \( \sim 10^3 \) TeV, beyond which the spectrum steepens. However, the direct evidence for particle acceleration to such energies is scarce. Radio emission from shell-type SNRs is the result of synchrotron radiation from shock-accelerated electrons, but these electrons have typical energies of order 10 GeV. It is only the recent discoveries of nonthermal X-ray emission from shell-type SNRs that have finally provided evidence of particles at energies of 10–100 TeV. The X-ray emission from SN 1006 (Koyama et al. 1995) and G347.3−0.5 (Koyama et al. 1997; Slane et al. 1999) is predominantly nonthermal, while that from Cas A, Kepler, Tycho, and RCW 86 (Allen, Gotthelf, & Petre 1999) is predominantly thermal but contains a nonthermal component as well. However, it may also be the X-ray emission that poses the most significant constraint on accepting SNRs as the source of cosmic rays at energies near the knee. The X-ray fluxes from all remnants fall below the extrapolation of their radio spectra, implying a steepening or cut-off of the electron spectrum at higher energies. The implied spectral cut-off energies appear to be well below the knee of the cosmic-ray spectrum (Reynolds & Keohane 1999). It is thus of considerable importance to identify new examples of shell-type SNRs for which the X-ray emission is largely nonthermal.

RX J0852.0−4622 was discovered by Aschenbach (1998) using data from the ROSAT All-Sky Survey. Situated along the line of sight to the Vela SNR, the emission stands out above the soft thermal emission from Vela only at energies above \( \sim 1 \) keV. Data from the ROSAT PSPC indicate a hard spectrum with either a hot thermal component with \( kT \approx 2.5 \) keV or a power-law component with photon index \( \Gamma \approx 2.6 \) (Aschenbach 1998). The remnant is circular with a diameter of \( \sim 2' \); the emission is particularly enhanced along the northern, western, and southeastern limbs. Hereafter, we use the designation G266.2−1.2 for this newly identified SNR.

As first noted by Aschenbach (1998), the radio emission from G266.2−1.2 is quite weak (\( S_\nu \approx 30–50 \) Jy at 1 GHz) with faint, limb-brightened emission similar to the X-ray morphology (Combi, Romero, & Benaglia 1999; Duncan & Green 2000). SN 1006 and G347 are also faint radio emitters, perhaps suggesting a general characteristic of remnants for which the X-ray flux is dominated by nonthermal processes.

Iyudin et al. (1998) reported the COMPTEL detection of 44Ti from the source GRO J0852−4642, which was tentatively associated with G266.2−1.2. If correct, this association would be profound; the very short 44Ti lifetime (\( \tau \approx 90 \) yr) would imply a very young SNR, and the large observed size would require that the remnant be very nearby as well. Estimates based on the X-ray diameter and \( \gamma \)-ray flux of 44Ti indicate an age of \( \sim 680 \) yr and a distance of \( \sim 200 \) pc (Aschenbach, Iyudin, & Schönfelder 1999). The hard X-ray spectrum would seem to support this scenario as well. The inferred temperature would imply a rapid shock that is consistent with a young SNR. However, as we show here, the hard X-ray emission is not from hot, shock-heated gas; it is nonthermal. Further, separate reanalysis of the COMPTEL data finds that the detection of G266.2−1.2 as a 44Ti source is only significant at the 2–4 \( \sigma \) confidence level (Schönfelder et al. 2000). In the absence of such emission, and given that
the X-ray emission is nonthermal, the nearby distance and young age may need to be reexamined.

2. OBSERVATIONS AND ANALYSIS

We have carried out X-ray observations of G266.2—1.2 with the Advanced Satellite for Cosmology and Astrophysics (ASCA). The remnant was mapped in seven distinct pointings, each of ~17 ks duration. The resulting image from the ASCA GIS detectors is illustrated in Figure 1 (see also Tsunemi et al. 2000). Bright emission along the northern and western shell is accompanied by a compact central source surrounded by diffuse emission. Additional enhanced emission along the southeast shell is seen in the ROSAT image (Aschenbach 1998) but was inadvertently missed in the mapping carried out here. Contours in Figure 1 correspond to soft emission ($E = 0.1$–$2.4$ keV) from the Vela SNR, as observed in the ROSAT All-Sky Survey. Standard screening processes were applied to data from both the GIS and SIS detectors, and spectra were extracted from distinct regions of the remnant. Regions outside the SNR shell in the northwestern pointing were used for background subtraction for the GIS and for SIS chips S0C1,2 and S1C0,3. For the other SIS chips, for which no local background was available, we extracted background spectra from the blank sky fields available from the ASCA Guest Observer Facility. Although these fields are at high Galactic latitude, and are thus not representative of our viewing direction (particularly given the contribution from Vela itself), we find that results from spectral fitting are quite similar with either background source.

In Figure 2, we present plots of the X-ray spectra from three regions along the rim of the remnant using the GIS detectors: (1) the bright northwest rim; (2) the northeast rim; and (3) the western rim. Spectra were extracted from circular regions with radius $\sim 10$ centered on the location of maximum brightness. Unlike the line-dominated thermal emission that one expects from a young remnant, the spectra are featureless and well described by a power law of index ~2.6. This is remarkably similar to that observed for G347.3—0.5 (Koyama et al. 1997; Slane et al. 1999), another shell-type SNR dominated by nonthermal emission. The index is flatter than that observed for SN 1006 ($\Gamma = 2.95 \pm 0.2$), the prototype of this class of nonthermal shell-type SNRs (Koyama et al. 1995), although this value was derived for only a portion of the remnant shell.

Because of the smaller field of view and the difficulty of merging spectra from different CCDs, the spectra from the SIS are somewhat sparse. However, there is still a clear lack of emission-line features. The spectra are still adequately described by an absorbed power law, although the best-fit parameters differ somewhat from those derived from the GIS observations. Given the better overall statistics, and the higher sensitivity to the high-energy end of the spectrum, we use the results from the GIS spectral fits in the discussion below.

Although we have applied a background subtraction to the GIS spectra, the soft thermal emission from the Vela SNR is spatially variable, and there is significant residual soft flux in some of the regions, as seen in Figure 2. We have modeled the emission with two components. A thermal model (Raymond & Smith 1977) was used to account for the soft emission, with the column density fixed at $10^{20}$ cm$^{-2}$, a typical value for the Vela SNR (Bocchino, Maggio, & Sciortino 1999; Aschenbach, Egger, & Trümper 1995). An absorbed power law was used for the hard emission. To emphasize the contribution from Vela, we have not included the thermal component in the spectral plots shown here.

The best-fit spectral parameters for G266.2—1.2 are summarized in Table 1. The temperature of the thermal component is similar to that observed for the hotter component of Vela (Bocchino, Maggio, & Sciortino 1999), as expected
since the GIS response is not well suited to detected the softer component at $\sim 0.1$ keV. The spectral indices for the emission regions along the shell of G266.2 – 1.2 are all consistent with a value of $\sim 2.6$.

The column density for the power-law component summarized in Table 1 is significantly higher than that for Vela. While simple scaling of the column density to estimate the distance to G266.2 – 1.2 is clearly rather uncertain, it would appear that the remnant is at least several times more distant than Vela. To provide some measure of the scaling of quantities, in discussions below, we express the distance as $d_1 = (d/1\text{ kpc})$. We note that the column density derived from PSPC data alone (Aschenbach 1998), although not well determined, is apparently lower than that measured here. Given the importance of the distance measurement, as we discuss below, it is of considerable interest to obtain improved measurements of the column density.

As shown in Figure 1, the central region of the remnant contains a compact source that we designate as AX J0851.9 – 4617.4. The image centroid is at R.A.$_{2000}$: $08^h51^m57^s$, decl.$_{2000}$: $-46^\circ17'24''$; the position uncertainty is roughly 2'' in each direction because of the low-resolution mode in which the GIS data were obtained. This source is surrounded by diffuse emission that extends toward the northwest. It is of considerable interest to speculate as to whether this represents a central neutron star surrounded by a synchrotron nebula. Such an association would be spectacular indeed, providing further evidence of a massive progenitor for the remnant and possibly constraining the age through modeling of the plerionic component. In Figure 3 we present the GIS spectrum for both AX J0851.9 – 4617.4 and the diffuse central region of the remnant. The diffuse emission is well described by a power law of spectral index $\sim 2.0$, again accompanied by a soft thermal component that we associate with Vela. Given the nonthermal nature of the shell emission, however, it is quite possible that the diffuse central emission is just associated with emission from the shell projected along the central line of sight. We note that the spectrum of this central emission appears somewhat harder than that from the rest of the remnant, perhaps suggesting a plerionic nature, but more sensitive observations are required to clarify this.

The GIS count rate for AX J0851.9 – 4617.4 is $\sim 0.04$ s$^{-1}$. The 14.6 ks GIS exposure (after screening) thus yields roughly 500 counts in each detector. The spectrum is thus rather sparse and can be adequately described by a variety of models. Two of particular interest are blackbody emission, as might be expected from the surface of a cooling neutron star or from the polar caps of a neutron star heated through particle acceleration in the magnetosphere, and a power-law spectrum that might result from emission directly from a neutron star magnetosphere. Best-fit spectral results from these models are summarized in Table 1.

### Table 1

| Region            | $kT$ (keV) | $N_H$ ($\times 10^{21}$ cm$^{-2}$) | $\Gamma$ (photon) | $F_\nu$ ($\times 10^{-12}$) |
|-------------------|------------|-----------------------------------|-------------------|-----------------------------|
| Northwestern rim  | $0.5^{+0.2}_{-0.3}$ | $4.0 \pm 1.8$ | $2.6 \pm 0.2$ | $4.2 \times 10^{-11}$ |
| Northeastern rim  | $0.6 \pm 0.1$ | $5.3^{+2.0}_{-0.9}$ | $2.6 \pm 0.2$ | $2.9 \times 10^{-11}$ |
| Western rim       | $0.5^{+0.2}_{-0.3}$ | $1.4^{+1.4}_{-1.4}$ | $2.5 \pm 0.2$ | $2.1 \times 10^{-11}$ |
| Center            | $0.7 \pm 0.1$ | $11.5^{+14.3}_{-10.2}$ | $2.0^{+0.5}_{-0.3}$ | $6.7 \times 10^{-12}$ |
| AX J0851.9 – 4617.4 |            |                                 |                  |                             |
| BB                | $0.47 \pm 0.04$ | $0.0^{+0.8}_{-0.8}$ | $...$ | $2.1 \times 10^{-12}$ |
| PL                | $...$ | $3.7^{+1.4}_{-1.4}$ | $3.2 \pm 0.5$ | $6.6 \times 10^{-12}$ |

* Power-law component only for SNR, in units of $10^{21}$ cm$^{-2}$.
* In ergs cm$^{-2}$ s$^{-1}$ (0.5–10 keV).
* Diffuse emission only.

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Fig. 3.—ASC A spectra from both GIS detectors for the central point source and surrounding diffuse region of G266.2 – 1.2. The diffuse emission is indistinguishable from that of the SNR shell. The point source spectrum is adequately described by a power law, but other models are possible as well.

3. Discussion

The prevalence of nonthermal X-ray emission in G266.2 – 1.2 suggests that the remnant is an efficient accelerator of particles. While thermal emission from swept-up material and shocked ejecta typically dominates the emission of shell-type SNRs, there are conditions that can lead to enhanced nonthermal X-ray emission. Recent models for nonlinear shock acceleration in SNRs (e.g., Ellison, Berezhko, & Baring 2000) show that the ambient density and magnetic field are critical parameters in determining the relative contributions of thermal and nonthermal elec-
trons in the X-ray emission. Low values of both quantities can yield a synchrotron-dominated remnant in X-rays, while a low magnetic field, in particular, also leads to an increased ratio of the TeV $\gamma$-ray to radio flux ratio. This scenario appears consistent with both SN 1006 and G347.3$-0.5$. The former is the remnant of a Type Ia explosion, for which the ejecta mass and ambient density are expected to be relatively low, and is located at a relatively high Galactic latitude, which is consistent with a low magnetic field. The latter, on the other hand, is in the Galactic plane and appears consistent with a massive star progenitor if the association with surrounding molecular clouds and a nearby H II region suggested by Slane et al. (1999) is correct. This, too, would then imply a low ambient density if the remnant has evolved in a stellar wind cavity, which is likely in such a scenario. Both remnants are observed in TeV $\gamma$-rays (Tanimori et al. 1998; Muraishi et al. 2000), and both are weak radio remnants (Stephenson, Clark, & Crawford 1977; Aschenbach 1998; Combi et al. 1999). We note, however, that the circumstances that lead to a dominant nonthermal contribution in the soft X-ray band are complicated. Reynolds (1998) has shown that the maximum nonthermal X-ray emission relative to the radio emission occurs when the remnant age is comparable to the electron loss time in the postshock magnetic field. However, this alone is not sufficient to guarantee that the thermal X-ray emission from shock-heated ejecta and interstellar material will not dominate the X-ray flux.

For G266.2$-1.2$, the ASCA observations clearly show that nonthermal processes dominate the X-ray emission. Our limit on the density of any thermally emitting material in the northwest region, where the emission is brightest, is $n_p < 2.9 \times 10^{-21} d_1^{-1/2} f^{-1/2} \text{cm}^{-3}$, where $f$ is the filling factor of a sphere taken as the emitting volume in the region extracted. Here we have assumed an equilibrium thermal model (Raymond & Smith 1977). Nonequilibrium ionization models can yield higher emissivities, which would lower the derived limit on the density. We note that this limit is restricted to gas with temperatures above 1 keV because of the severe contributions of soft thermal emission from the Vela SNR; higher densities of cooler material in G266.2$-1.2$ cannot be ruled out. Observations of the brightest shell regions with high angular resolution, so as to minimize these contributions, are of considerable interest to further constrain the ratio of thermal to nonthermal emission.

If G266.2$-1.2$ is actually a source of $^{44}$Ti at levels indicated by the COMPTEL measurements, so that the age and distance estimates suggested by Aschenbach et al. (1999) and others are correct, then the ambient density is extremely low. The reported $\gamma$-ray line flux would indicate a massive star progenitor, and the low density would then imply the presence of a stellar-wind cavity such as that inferred for G347.3$-0.5$.

CO data (May, Murphy, & Thaddeus 1988) reveal a concentration of giant molecular clouds—the Vela Molecular Ridge—at a distance of $\sim 1-2$ kpc in the direction of Vela. The presence of OB and R associations, as well as H II regions, demonstrate that these clouds are sites of recent star formation. The bulk of the CO emission along the line of sight to G266.2$-1.2$ is concentrated in a velocity range $v_{\text{LSR}} = 0.7-9.8 \text{ km s}^{-1}$ (Murphy & May 1991) and extends down to a Galactic latitude of $b \approx -1.2$. The total column density through the ridge is in excess of $10^{22} \text{ cm}^{-2}$, with the northeast rim of G266.2$-1.2$ (nearest the Galactic plane) falling along the steeply increasing column density region of the ridge while the western rim lies along a line of much lower column density (Fig. 4); the CO column density varies by more than a factor of 6 between these regions. The lack of a strong variation in $N_H$ across G266.2$-1.2$ indicates that the remnant cannot be more distant than the Vela Molecular Ridge. On the other hand, if $N_H$ is much larger than for the Vela SNR, as the GIS data reported here indicate, then G266.2$-1.2$ must be as distant as possible consistent with being in front of most of the Molecular Ridge gas. This is consistent with an interpretation in which G266.2$-1.2$ is the product of a massive progenitor from this star-forming region and that the remnant evolution has proceeded in the presence of a wind cavity, leading to a low ambient density much like that indicated for G347.3$-0.5$.

The angular size of G266.2$-1.2$ gives a free-expansion age of $t \sim 3.4 \times 10^3 v_{\text{sh}}^{-3/4} d_1^{1/2} \text{ yr}$, where $v_{\text{sh}}$ is the expansion velocity in units of 5000 km s$^{-1}$. Alternatively, using the limit on the preshock density derived above, the Sedov age of the remnant is $t < 3.9 \times 10^3 d_1^{-3/4} f^{1/2} E_{51}^{1/2} \text{ yr}$, where $E_{51}$ is the kinetic energy from the explosion in units of $10^{51}$ ergs. In either case, the remnant is relatively young, although ages as young as those based on the $^{44}$Ti lifetime would require either an extremely large expansion velocity or an extremely low ambient density unless the remnant distance is actually much less than 1 kpc.

We note that the $E = 1.156$ MeV $\gamma$-rays that announce the presence of $^{44}$Ti are actually secondary products. The decay of $^{44}$Ti proceeds via electron capture to form $^{44}$Sc, which then decays rapidly to $^{44}$Ca, producing the observed $\gamma$-rays. As electrons fill the vacancy created by the electron capture, we expect Sc-K emission of X-rays at $E = 4.1$ keV. Using the fluorescence efficiency of 19% (Krause 1979), we expect a flux $F(\text{Sc-K}) \sim (6.6 \pm 1.3) \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$ based on the $^{44}$Ti flux of Iyudin et al. (1998). We have searched the ASCA SIS data for evidence of such a line feature but have found no compelling evidence to support its presence. The SISO spectrum of one region along the northwestern rim contains a feature at $\sim 4$ keV (Fig. 5) but is not seen in the

![Fig. 4.—CO emission ($V_{\text{LSR}} = -5$ to $+20 \text{ km s}^{-1}$) along the line of sight to G266.2$-1.2$. Contours correspond to the X-ray emission from the remnant as seen in Fig. 1. Note the use of Galactic coordinates to emphasize orientation relative to the Galactic plane.](image-url)
derive a 1 at the 99% confidence level. We set an upper limit to the pulsed fraction of 45%-70% for frequencies from $10^{-3}$ to $10^{3}$ Hz.

Finally, we note that the spectrum of the diffuse emission in the central region of the remnant is consistent with a power law with an index similar to the Crab nebula and other synchrotron nebulae associated with supernova remnants. The ratio of the point-source flux to that of the diffuse surrounding emission is $\sim$40%, which is similar to that for the Vela pulsar and its associated synchrotron nebula. It is of interest that the Vela pulsar also has a soft spectrum best characterized as blackbody emission from heated polar caps (Ögelman, Finley, & Zimmermann 1993). High-resolution radio observations of the central region of G266.2–1.2 using the Australia Telescope Compact Array reveal a faint, slightly extended ($\sim$45° across) source within the error circle of AX J0851.9–4617.4 (B. Gaensler, 2000, private communication). The 1.4 GHz flux density of this source is $\sim$2 mJy, however, which is substantially lower than seen for known synchrotron nebulae, and the X-ray luminosity is quite low as well. Further observations are required to better understand the nature of this source.

4. CONCLUSIONS

The ASCA observations of G266.2–1.2 reveal that the soft X-ray emission from this SNR is dominated by nonthermal processes. This brings to three the number of SNRs in this class and provides additional evidence for shock acceleration of cosmic rays in SNRs. Because of the bright and spatially varying background caused by the Vela SNR, limits on the thermal emission from G266.2–1.2 are difficult to establish. As a result, its evolutionary state is poorly constrained. However, the ASCA data reveal a larger column density for this remnant than for Vela, indicating that G266.2–1.2 is at a larger distance and perhaps associated with the star formation region located at a distance of 1–2 kpc. The very strong ratio of nonthermal to thermal X-ray emission argues for a low-density environment, possibly suggesting evolution in a stellar wind cavity. Such a scenario would indicate a massive progenitor, from which one could expect a relic neutron star. The point source AX J0851.9–4617.4 could represent this source, with the diffuse emission around the source being an associated synchrotron nebula, albeit a very faint one. Higher resolution X-ray observations of this source are of considerable importance in order to assess its relationship to the SNR.

We note that TeV $\gamma$-ray emission has been detected from both SN 1006 and G347.3–0.5, confirming the presence of very energetic electrons in these remnants. Similar observations of G266.2–1.2 are clearly of considerable interest as well.

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