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Violent evolution of supernova remnants as revealed by Chandra and XMM-Newton

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Abstract. Recent Chandra and XMM-Newton observations have directly revealed evolution of young supernova remnants (SNRs), i.e., expansions and year-scale spectral variations. We show that expansions can be used to infer basic parameters of SNRs such as the age, the distance, and the density: Vela Jr. turns out to be located $\gtrsim$750 pc away and 1000–3000 yr old, and the ambient density around the northeastern rim of SN1006 is found to be $0.085^{+0.055}_{-0.035}$ cm^{-3}. In addition, Chandra confirms a paradoxical difference in expansion rates for Cas A measured in the different wave bands. On the other hand, Chandra-based expansions for Kepler and Tycho are found to disagree with the previous ROSAT/Einstein-based expansions, but be consistent with radio expansions.
Year-scale flickering of filaments is discovered in RX J1713.7-3946 and Cas A. It is considered to be possible evidence of extremely fast acceleration/cooling of relativistic electrons in a strongly amplified magnetic field to the level of mG-scale. Also, global flux decline and spectral steepening are found in Cas A, whereas no such spectral variations are detected in SN1006.

1. Introduction

The aftermath of catastrophic supernova explosions, supernova remnants (SNRs), strongly influence the evolving universe, not only supplying energies, heavy elements, and cosmic rays, but also inducing star formations. Thus, studying SNR evolution is fundamentally important in astrophysics. In principle, comparisons of multi-epoch observations give us direct opportunities for such studies. However, in practice, long distances to SNRs and hence their small apparent sizes make things difficult; there were only limited number of studies especially in X-rays (e.g., Koralesky et al., 1998).

This situation dramatically changed with the X-ray observatories Chandra and XMM-Newton which are capable of superior angular resolution imaging. The two satellites observed many bright SNRs in their initial years after launch, revealing unprecedented clear X-ray images. Over the last several years, follow-up observations have made it possible to find real-time evolution of SNRs, including the expansion of the forward shock front as well as year-scale spectral variations. In many cases, the results are surprising and have significant im-

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plications. We here intend to summarize them briefly, from an observational point of view.

2. Expansion measurements

2.1. First expansion measurements of Vela Jr. and NE SN1006

Vela Jr. was discovered by ROSAT all-sky survey in the direction of the southeastern corner of the Vela SNR, from a high-energy (above 1.3 keV) band image (Aschenbach, 1998). Figure 1 (a) shows the ROSAT image covering the entire Vela Jr., from which we can see the remnant as a clear circle with a large radius of $\sim 60'$. Interestingly, the discovery of Vela Jr. was accompanied by a report of the COMPTEL detection of γ-ray line emission from ^{44}Ti (Iyudin et al., 1998), suggesting that this new remnant is very young and nearby because of the short lifetime ($\tau \sim 90$ yr) of ^{44}Ti. (Note that Mochizuki et al. (1999) suggested a longer effective lifetime due to a high degree of ionization of ^{44}Ti by the reverse shock heating.) Based on both X-ray and γ-ray data, the age and the distance are estimated to be $\sim$680 yr and $\sim$200 pc, respectively (Aschenbach et al., 1999). Most of the follow-up works support this young age (Tsunemi et al., 2000; Iyudin et al., 2005; Bamba et al., 2005). Near the center of Vela Jr., there is a bright compact object, AX J0851.9-4617.4, which is suspected to be a central-compact object (CCO) of Vela Jr. Its age is, however, estimated to be a few thousands yr. The age discrepancy between Vela Jr. and the candidate CCO remained a mystery.

XMM-Newton has been observing the northwestern (NW) rim of Vela Jr. for both calibration and scientific purposes. A hard X-ray (1.5–8 keV) XMM-Newton image in Fig. 1 (b) shows sharp edges of the remnant. Katsuda et al. (2008a) performed a proper-motion measurement using the 2001, 2003, 2005, and 2007 observations, which yields a maximum time difference of 6.5 yr. The difference of the 2001 and 2007 images is shown in Fig. 1 (c). We can clearly see a black (negative) narrow line running from the northeast (NE) to the southwest (SW) as a result of the shock-front motion. Note that other black or white lines are due to artificial effects such as bad columns or gaps of CCD chips. A quantitative measurement of the shift of the X-ray filament was then performed based on projected one-dimensional profiles. To this end, a northern portion of the NW filament was selected (see, Fig. 1 (b)), since this region was almost free from artificial effects. The image of this region was collapsed along the radial axis of the SNR, resulting in projected one-dimensional profiles plotted in Fig. 1 (d). We can clearly see the outward motion of the shock front. The shift is measured to be $0''.84 \pm 0''.23\,\mathrm{yr}^{-1}$, leading to an expansion rate of $0.023 \pm 0.006\,\%\,\mathrm{yr}^{-1}$. The expansion rate is about one seventh of that expected for free expansion, i.e., $1°/680$ yr assuming the age of 680 yr. This expansion rate is surprisingly low, given that Vela Jr. is as young as 680 yr old.

Comparing the expansion rate with those of other young historical SNRs, Katsuda et al. (2008a;2009a) inferred the age of Vela Jr. to be 1000-3000 yr. In addition, the distance to the remnant is obtained to be 740 $(\upsilon/3{,}000\,\mathrm{km\,s^{-1}})(\mu/0''.84\,\mathrm{yr}^{-1})^{-1}$ pc, where υ is the actual shock velocity and μ is the proper motion of the shock. Given that X-ray emission from Vela Jr. is totally nonthermal in origin, the actual shock velocity of $3000\,\mathrm{km\,s^{-1}}$ would be taken as a lower limit. Thus, the distance of 740 pc should be considered to be a lower limit as well. In this way, the expansion rate of the NW rim suggests an older age and a larger distance than those previously estimated.

If we take into account these suggestions, the detection of ^{44}Ti from Vela Jr. (Iyudin et al., 1998) cannot be realistic; the initial mass of ^{44}Ti is estimated to be comparable to a solar mass which is at least three orders of magnitude larger than that expected in nucleosynthesis models (e.g., Thielemann et al., 1996; Rauscher et al., 2002). Therefore, ^{44}Ti gamma-ray emission detected by COMPTEL is most likely related to something other than Vela Jr. Otherwise, the detection itself should be reconsidered. In fact, a separate reanalysis of the COMPTEL data finds that the detection of this remnant as a ^{44}Ti source is only significant at the 2-4 sigma level (Schönfelder et al., 2000). Meanwhile, the revised age and distance strongly support the association between

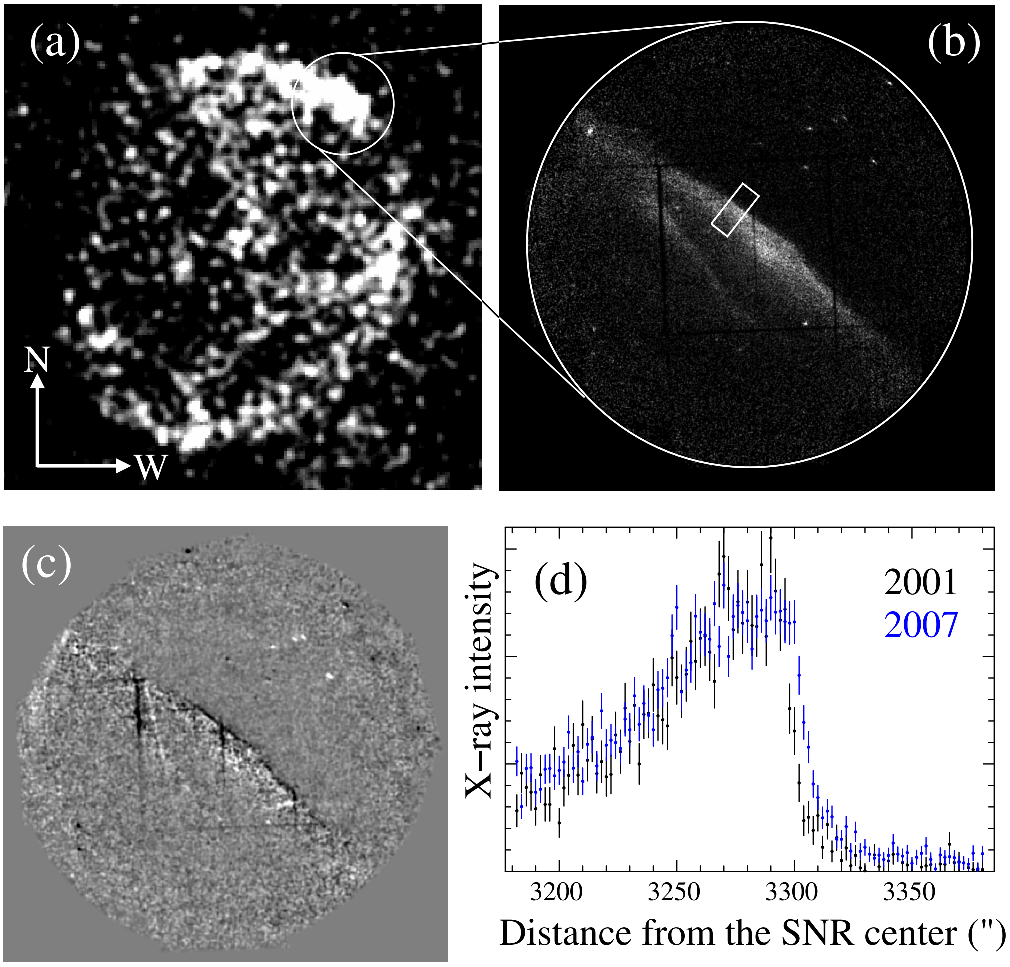

Fig. 1. (a): ROSAT all-sky survey image of Vela Jr. (1.3–2.4 keV). A white circle on the NW rim is a field of view of XMM-Newton used for a proper-motion measurement. (b): XMM-Newton image of the NW rim of Vela Jr. (1.5–8.0 keV). A white box is where one-dimensional profiles are extracted. (c): Difference image between 2001 and 2007 from XMM-Newton. The shock-front motion can be seen as a narrow black filament running from NE to SW. Note that other black/white filamentary structures are due to either gaps of CCD chips or bad columns. (d): Projected one-dimensional X-ray profiles of the white box region in Fig. 1 (b). Black and blue are responsible for 2001 and 2007 observations, respectively.

Vela Jr. and the candidate CCO, AX J0851.9-4617.4.

Turning to SN1006, it is very famous as the first SNR that provided us with evidence for diffusive shock acceleration of electrons to TeV energies (Koyama et al., 1995). Since then, it has been unrivaled laboratory for the study of particle acceleration; e.g., the discovery of narrow nonthermal filaments at the forward shock (Long et al., 2003; Bamba et al., 2003), nondetection of X-ray precursors (Long et al., 2003; Morlino et al., 2010), and detection of TeV gamma-rays (Acero et al., 2010).

In 2008, Chandra performed the second-epoch observation of the NE rim to measure proper motions. Combining with the first-epoch observation taken in 2000, Katsuda et al. (2009b) found a proper motion of forward shocks to be $\sim 0''.48\,\mathrm{yr}^{-1}$. They also found that the proper motion does not vary around the NE rim within the 10% measurement uncertainties. Assuming pressure equilibrium around the periphery from the thermally dominated NW rim to the nonthermal dominated NE rim, the ambient density at the NE SN1006 was derived to be $0.085^{+0.055}_{-0.035}\,\mathrm{cm}^{-3}$. This was the first density estimate in this region, where thermal emission is so faint that spectroscopy of thermal emission is hard to perform. The ambient density is a key parameter to control emission mechanisms of TeV gamma-rays. However, unfortunately, no conclusive result has yet derived (Acero et al., 2010), even by taking into account the ambient density inferred. Both detailed modeling and more observational data would help us understand the nature of particle acceleration in SN1006.

2.2. Multiwavelengths expansion measurements of Cas A, Kepler, and Tycho

Expansion measurements for very young SNRs, Cas A, Kepler, and Tycho, have been performed in multiwavelengths from radio to X-rays. Among them, X-ray measurements that started most recently posed a paradoxical puzzle: X-ray expansions are about twice faster than those for radio (Kepler: Hughes (1999), Tycho: Hughes (2000), Cas A: Thorstensen et al. (2001). Since all the X-ray measurements were based on ROSAT and Einstein data, remeasurements using Chandra with superior spatial resolution were eagerly being awaited.

DeLaney & Rudnick (2003) were the first who tackled this issue. They obtained a second-epoch observation of the Cas A SNR with Chandra, and performed proper-motion measurements for nonthermal dominated filaments located around the edge of the SNR. The median value of their expansion rates was derived to be $0.21\,\%\,\mathrm{yr}^{-1}$. This is equal to the result from Einstein and ROSAT, and thus confirms the paradox in multiwavelength expansions. The difference may indicate various degrees of deceleration for the material emitting in those wave bands (DeLaney & Rudnick, 2003).

Katsuda et al. (2008b) and Vink et al. (2008) measured expansions of Kepler, focusing on the outermost rim and the inner regions, respectively. As a result, it turned out that the Chandra-based X-ray expansion rates (0.1–$0.25\,\%\,\mathrm{yr}^{-1}$ varying with azimuthal angle) are fully consistent with radio measurements. Katsuda et al. (2010a) also revealed for Tycho that X-ray expansions by Chandra are consistent with those from radio and optical. Whereas these results solve the paradoxical expansion rates in X-ray and radio, the Chandra-based expansions are apparently discrepant with the previous ROSAT/Einstein-based measurements (Hughes, 1999, 2000). The reason of the discrepancy is still unclear. One possibility is the energy sensitivity difference between ROSAT/Einstein and Chandra. ROSAT and Einstein have no sensitivity above 2.4 keV, while Chandra is sensitive up to 10 keV. Therefore, it is easier for Chandra to define the forward shock front (the outermost edge of the SNR) than for ROSAT, given that forward shocks are dominated by nonthermal emission which shows a hard X-ray spectrum. In addition, it should be, of course, noted that Chandra has superior angular resolution of $\sim 0''.5$ half-power, about 16 times better than that of ROSAT/Einstein.

3. Year-scale spectral variations

Exciting results also derived by recent Chandra observations of SNRs are rapid (year-scale) brightness changes of small-scale ($\sim 10''$) X-ray nonthermal filaments. So far, only RX J1713.7-3946 (Uchiyama et al., 2007) and Cas A (Patnaude & Fesen, 2007, 2009; Uchiyama & Aharonian, 2008) are known to exhibit such features. Some filaments show flux increases by a factor of ~ 2, whereas some completely faded away. The rapid brightening or decline were, respectively, interpreted as the results of extremely fast acceleration or cooling in mG-scale magnetic field (Uchiyama et al., 2007). Thus, the flickering are thought to be imprints of strongly amplified magnetic field at SNR shocks. An alternative explanation considers magnetic field fluctuation due to plasma waves behind the shock front (Bykov et al., 2008).

More recently, it was found that not only small-scale features but also larger scale X-ray–emitting regions show short-term X-ray brightness changes: the 4.2–6.0 keV X-ray emission from the global Cas A SNR declines steadily by $\sim$1.5–2% yr^{-1} between the years 2000 and 2010 (Patnaude et al., 2011). In addition, spectral analyses revealed that nonthermal spectral power-law index has steepened from $\sim$2.8 in 2000 to $\sim$3.1 in 2010. The authors showed that the observed decline and steepening of the nonthermal X-ray emission is consistent with a deceleration of the remnant's $\sim$5000 $\mathrm{km\,s^{-1}}$ forward shock of $\sim$30–70 $\mathrm{km\,s^{-1}\,yr^{-1}}$.

Finally, we point out that Katsuda et al. (2010b) failed to detect significant spectral variations between 2000 and 2008 in the synchrotron emission of NE SN1006, which is in stark contrast to RX J1713.7-3946 and Cas A. A difference between SN1006 and the other two SNRs is the smoothness of surface brightness. SN1006 is located at high Galactic latitude where small-scale cloudlets are not present. Additionally, SN1006 as a Type Ia remnant is interacting with undisturbed interstellar medium instead of the stellar wind of the progenitor as is likely for the other two objects. Thus, short-term spectral variations may be caused by interactions between SNR shocks (most likely, forward shocks) and complicated, clumpy ambient medium.

4. Conclusions

With the superior spatial resolution of Chandra and XMM-Newton, it has recently become possible to directly observe the dynamics and evolution of SNRs by comparing observations separated by a few years. We have shown that expansion measurements can be a powerful tool to infer basic parameters of SNRs such as the age, the distance, and the ambient density. Also, year-scale spectral variations provided us with new opportunities to understand particle acceleration physics in SNRs. These studies has just started. We expect more exciting results in the next few years.

5. Discussion

RALF NAPIWOTZKI: Could the discrepancy between X-ray and radio proper motions be explained by one energy band measuring a pattern velocity (e.g., a shock moving through matter) and the other matter velocity?
SATORU KATSUDA: In Cas A, the X-ray expansion is measured to be roughly twice higher than radio. This difference cannot be explained by the difference between the pattern (shock) velocity and the matter velocity. It is likely that there are various degrees of deceleration for the material emitting in those wave bands, as was suggested by DeLaney & Rudnick (2003).

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