FAST VARIABILITY OF NONTHERMAL X-RAY EMISSION IN CASSIOPEIA A: PROBING ELECTRON ACCELERATION IN REVERSE-SHOCKED EJECTA

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ABSTRACT

Recent discovery of the year-scale variability in the synchrotron X-ray emission of the supernova remnant (SNR) RX J1713.7−3946 has initiated our study of multiepoch X-ray images and spectra of the young SNR Cassiopeia A based on the Chandra archive data taken in 2000, 2002, and 2004. We have found year-scale time variations in the X-ray intensity for a number of X-ray filaments or knots associated with the reverse-shocked regions. The X-ray spectra of the variable filaments are characterized by a featureless continuum, and described by a power law with a photon index within 1.9–2.3. The upper limits on the iron K-line equivalent width are 110 eV, which favors a synchrotron origin of the X-ray emission. The characteristic variability timescale of 4 yr can be explained by the effects of fast synchrotron cooling and diffusive shock acceleration with a plausible magnetic field of 1 mG. The X-ray variability provides a new effective way of studying particle acceleration at supernova shocks.

Subject headings: acceleration of particles — ISM: individual (Cassiopeia A) — radiation mechanisms: nonthermal

1. INTRODUCTION

The young (∼330 yr old) supernova remnant (SNR) Cassiopeia A (Cas A) is a unique astrophysical laboratory for studying high-energy phenomena in SNRs because of its brightness across the entire electromagnetic spectrum from radio (e.g., Baars et al. 1977) to very high energy gamma rays (Aharonian et al. 2001; Albert et al. 2007). While the X-ray emission of Cas A below 3 keV is dominated by line emissions from the thin thermal plasma of the shocked ejecta, as demonstrated by observations with ASCA (Holt et al. 1994), a prominent nonthermal tail is known to be present and dominant above 10 keV (Allen et al. 1997; Favata et al. 1997).

Nonthermal X-rays appear to be emitted mainly from fragmented filaments or knots in reverse-shocked regions. The bulk of the hard X-ray emission in 10–12 keV from Cas A comes from such components; the total emission in the outer peripheral filaments found by Chandra (Hughes et al. 2000; Vink & Laming 2003) is only a small fraction of the total 4–6 keV continuum flux (Bleeker et al. 2001). The interpretation of the nonthermal component in reverse-shocked ejecta remains an open issue (e.g., Laming 2001).

In this Letter, we present the analysis of multiepoch Chandra imaging and spectrometric data of Cas A. This work was motivated by our recent discovery of time variability in the synchrotron X-ray emission of SNR RX J1713.7−3946 (Uchiyama et al. 2007), where the year-scale time variability requires, most likely, the presence of a largely amplified magnetic field of 1 mG in compact filaments. The strength of magnetic field in the compact radio knots in Cas A is estimated to be 1–3 mG (Atoyan et al. 2000), just sufficient to produce year-scale variability through synchrotron cooling and shock acceleration of multi-TeV electrons. Indeed, here we report significant time variations in nonthermal X-ray emission from many compact regions. The distance to Cas A is assumed to be 3.4 kpc (Reed et al. 1995) so the angular scale of 1′ corresponds to 1 pc.

2. DATA

We analyzed the X-ray data obtained with the ACIS-S3 chip on 2000 January 30 (Hwang et al. 2000; Gotthelf et al. 2001), 2002 February 6 (DeLaney & Rudnick 2003), and 2004 February 8 (Hwang et al. 2004), each with ≈50 ks exposure. Table 1 gives the log of the Chandra observations. The observations were made with ACIS-S3 in the graded mode, with which telemetry size can be reduced. The three observations have almost identical configuration such as the aim point and the roll angle, allowing us to directly compare the three images without taking account of the varying point-spread functions (PSFs). The aim point is located ∼1.9′ southeast of the central point source, the compact remnant left behind after the supernova explosion.

The X-ray analysis was done using the CIAO software package (version 3.4). We reprocessed the event data, applying standard data reduction with the latest calibration files. We find that the sky coordinates of the central point source in the three epochs are consistent with each other with an accuracy of ±0.2″. The point source itself is estimated to be moving at an angular speed of ≈0.02″ yr−1 (Thorstensen et al. 2001), thus 0.08″ in the 4 yr span.

Figure 1 shows the Chandra image (with 0.2″ × 0.2″ pixels) of Cas A in the 4–6 keV band averaged over the three epochs. This energy band corresponds to the continuum emission between Ca and Fe K lines, comprised of thermal bremsstrahlung and nonthermal component(s). Assuming that the hard X-ray above 10 keV is dominated by nonthermal radiation processes, we estimate about 50% of 4–6 keV photons should be of nonthermal origin. Filamentary structures having high surface brightness in the continuum band are found only for radii less than 2′ (referred as inner filaments), implying their association with the reverse shock as is shown to be the case by Helder & Vink (2008).

We are interested here in the nonthermal X-ray components. We selected the two boxes shown in Figure 1 based on the following criteria. First, we identified regions sufficiently bright...
TABLE 1

| ID  | Obs. ID | Date       | R.A. (deg) | Decl. (deg) | Roll (deg) | Exposure (ks) |
|-----|---------|------------|------------|-------------|------------|---------------|
| P1  | ......  | 2000 Jan 30| 350.9176   | 58.7934     | 323.4      | 49.9          |
| P2  | ......  | 2002 Feb 06| 350.9172   | 58.7938     | 323.4      | 49.9          |
| P3  | ......  | 2004 Feb 08| 350.9188   | 58.7949     | 325.5      | 49.5          |

Notes.—Sky coordinates are right ascension (R.A.) and declination (Decl.) in J2000.0, representing the pointing direction. The exposure time is the net integration time after standard filtering.

in the 4–6 keV band, exceeding 3 counts pixel\(^{-1}\) at least in one epoch, in order to obtain statistics enough for a variability search. Note that this condition is met only by the inner filaments, associated with the reverse shock or its secondary shocks. The second requirement is that the level of the continuum emission is high relative to the silicon line strength. Specifically, we calculated the ratio of 4–6 keV counts to 1.7–2.2 keV counts at each pixel, and selected those regions having the ratio exceeding 0.5. In this way, we found that the inner filaments satisfying these criteria are distributed inside the two boxes only. Since we do not aim at constructing a statistical sample in this work, we adopted these simple criteria, accounting for neither position-dependent PSFs nor effective area.

3. ANALYSIS

Figure 2 displays a sequence of three-epoch 4–6 keV images of the central box (left) and the western box (right), each with dimensions of 0.5′ × 1′. Morphologically distinctive components that satisfy the criteria mentioned above are labeled as A, B, C, E, G, and H. Also we tagged an additional two features, D and F.

The 4–6 keV images over a 4 yr time interval reveal a dozen time-variable structures. Region C has decreased by a factor of 2 from 2000 to 2004. Region H underwent a flux brightening by 50% over the time interval of 4 yr. (By measuring the silicon line flux from the compact ejecta features, we estimated a systematic error in the flux measurements to be <9%.) The variable filaments are spatially extended beyond Chandra's PSFs, typically ~3″–5″ in length and ~1″ in width. Also, some filaments that we did not label, such as those in the south of region C, exhibit time variability. Year-scale time variability appears to be the prevailing nature in the bright filaments or knots in the 4–6 keV band.

Before investigating the epoch-dependence of the spectral parameters, we first constructed X-ray spectra averaged over the three epochs. Regions A and B were combined into a single zone, and regions D, E, F, and G were merged. The background spectrum taken from a nearby, low-brightness region was subtracted from each spectrum. Since the choice of a background region largely affects the low-energy part of the X-ray spectrum of region H, photons below 3 keV were discarded for this region. The four X-ray spectra (A+B, C, D+E+F+G, and H) in the 1–8 keV band are shown in Figure 3. They all appear to be lineless.
Four out of the eight regions exhibit large time variations in Table 2. Figure 4 shows the time sequence of the model. The absorbing column density was fixed at a relevant labeled region at each epoch was fit by an absorbed power-law and spectral shape, the X-ray spectrum extracted from each region showing thermal spectra (e.g., Laming & Hwang 2003). More- recently, Patnaude & Fesen (2007) have reported X-ray variability in compact thermal knots, resulting from the passage of reverse shock over the ejecta clumps. In the entire face of the remnant, they identified six time-varying structures; all but one region (their R4, corresponding to our region C) were modeled by a “thermal” spectrum, specifically by a non-equilibrium-ionization plasma with an electron temperature of ~1 keV. On the other hand, we found a comparable number of variable “nonthermal” features just inside the two small boxes, by making use of 4–6 keV maps which are sensitive to non-thermal variability. Moreover, if we apply our criteria of significant variability, >10% yr⁻¹, to the Patnaude & Fesen (2007) sample, only two features remain. We conclude that variable nonthermal features are much more prevailing than the thermal ones.

Cas A is a very bright nonthermal radio source which indicates the presence in the remnant of relativistic electrons with a Lorentz factor $\gamma \geq 100$. The same electrons produce also high energy $\gamma$-rays through relativistic bremsstrahlung. Since the gas density in Cas A is known quite well, the $\gamma$-ray flux is robustly controlled by the strength of the magnetic field. Therefore, high energy $\gamma$-ray observations, combined with radio data, can provide reliable measurements of the magnetic field (Cowies & Sarkar 1980). A simple homogeneous model based on the radio observations and the upper limits of the $\geq 100$ MeV flux reported by the EGRET collaboration (Esposito et al. 1996) yields a lower limit on the magnetic field of 0.4 mG (Atoyan et al. 2000). In a more sophisticated two-zone model of Atoyan et al. (2000) the magnetic field in the compact radio knots, where particle acceleration is supposed to be taking place, is constrained to be $B = 1–3$ mG. These values would

| ID   | $N_H$ ($10^{22}$ cm⁻²) | $\Gamma$ | $F_{\text{5–10 keV}}$ ($10^{-12}$ ergs cm⁻² s⁻¹) | $\chi^2$ (dof) |
|------|------------------------|---------|-----------------------------------------------|---------------|
| AB   | 2.00 ± 0.10 2.31 ± 0.08 | 1.59 ± 0.04 | 0.85 (274) | |
| C    | 1.80 ± 0.13 2.37 ± 0.11 | 0.77 ± 0.03 | 1.08 (221) | |
| DEFG | 1.69 ± 0.06 2.24 ± 0.05 | 5.21 ± 0.05 | 0.98 (365) | |
| H    | 1.80 (fix) 1.97 ± 0.10 | 3.06 ± 0.07 | 0.84 (206) | |

Notes.—Fitting X-ray spectrum by a power law with photoelectric absorption. Absorbing column density $N_H$, photon index $\Gamma$, and unabsorbed 2–10 keV flux $F_{\text{5–10 keV}}$ are shown with 90% errors.

* X-ray energy below 3 keV is excluded from the fit and the absorbing column density is fixed at $N_H = 1.8 \times 10^{22}$ cm⁻².

In order to track the time variations in terms of both intensity and spectral shape, the X-ray spectrum extracted from each labeled region at each epoch was fit by an absorbed power-law model. The absorbing column density was fixed at a relevant value in Table 2. Figure 4 shows the time sequence of the unabsorbed X-ray flux normalized by that in the year 2000. Four out of the eight regions exhibit large time variations (>10% yr⁻¹). The time sequence of photon index $\Gamma$ for each region is also presented in Figure 4. We found notable variations of $\Gamma$ in two cases, regions F and H. Region H gives the hardest index of $\Gamma = 1.85 \pm 0.10$ in 2000, suggesting a direct link between flux increase and spectral hardening.

4. DISCUSSION

We have found that a half (4/8) of the filamentary regions that were selected simply by their brightness and hardness, showed a year-scale variability in X-ray flux. The X-ray spectra of the selected regions in the 1–8 keV range are featureless and well fit by an absorbed power law with a photon index $\Gamma \approx 1.9–2.4$. Given the absence of emission lines, we prefer to attribute the nonthermal X-ray emission in regions A–H to synchrotron radiation by very high-energy electrons. Synchrotron X-ray filaments or knots would originate in slightly overdense ejecta, say by a factor of ~2, into which a reverse shock (or transmitted shocks) with a typical shock speed of ~1000 km s⁻¹ has been driven (see Laming & Hwang 2003).
reasonably be applicable to the X-ray filaments, which have a similar size with the radio features, and are also presumed to be the sites of efficient particle acceleration by reverse (or secondary) shocks.

It is interesting to ask whether the X-ray flux changes are attributable solely to the changes in magnetic field strength. If so, it is expected that a substantial flux change in synchrotron X-rays accompanies a marked change in radio intensity. While the radio flux is proportional to $B^2$, the X-ray flux has weaker dependence on $B$, because X-rays are emitted in a quasi-saturated regime. Therefore one would expect stronger variations in the radio than in the X-ray band. According to Anderson & Rudnick (1995) however, among about 70 bright radio compact knots exceeding 20 mJy beam$^{-1}$, none showed a brightness increase larger than $+10\%\ yr^{-1}$ in the archive Very Large Array data at 5 GHz. A typical rate of brightening is about $+3\%\ yr^{-1}$, corresponding to an $e$-folding time of $\sim 30\ yr$, which is much longer than the X-ray variability timescale of 4 yr. Therefore it is more likely that the observed time variations are caused mainly by a rapid increase or decrease in the density of X-ray-emitting electrons. (The increase in the radio-electron density above the “sea” level is expected to be less significant, provided that fresh electrons have a harder energy spectrum than old electrons.) Indeed, as we argue below, the known constraint on $B$ provides the synchrotron cooling time being compatible with the observed time variability.

We have reported a similar X-ray variability in SNR RX J1713.7$-$3946, and attributed it to fast synchrotron cooling and shock acceleration of electrons (Uchiyama et al. 2007). Let us examine the observed variability timescale, using the equations presented in Uchiyama et al. (2007). Synchrotron cooling time is given by $t_{\text{syn}} \sim 1.5 \frac{B_{\text{mag}}}{\sqrt{B}} \frac{t_{\text{var}}}{\sqrt{h}}$, where $B_{\text{mag}}$ is the magnetic field strength in units of mG and $t_{\text{var}}$ is the mean synchrotron photon energy in units of keV. For $B \sim 0.5$ mG, the synchrotron cooling timescale becomes comparable to the variability timescale, $t_{\text{syn}} \sim t_{\text{var}} \sim 4$ yr. Therefore, even a magnetic field of 0.4 mG is able to explain the observed variability. For $B \sim 2$ mG, if the injection of relativistic electrons responsible for the synchrotron X-rays has recently ceased in a filament, the X-ray flux can be reduced on a timescale of $t_{\text{syn}} \sim 0.5$ yr. If the electron injection rate (i.e., the number of particles picked up and injected into the acceleration process in unit time) decreases noticeably in 4 yr, the number of X-ray-emitting electrons and consequently X-ray intensity can drop as observed. We note that plasma characteristics at shocks may change on a timescale of a few years given the arcsecond-scale size of the thermal ejecta filaments.

Rising flux is a signature of ongoing production (acceleration) of synchrotron-emitting electrons with energies of $\sim 10$ TeV. It implies that electron energy can increase to $\sim 10$ TeV in 4 yr or less at the shock. Assuming that electrons are accelerated via diffusive shock acceleration, the acceleration time of the X-ray-emitting electrons is given by $t_{\text{acc}} \sim 9\eta B_{\text{mag}}^{1/2} \frac{t_{\text{var}}}{\sqrt{h}} V_{1000}^{-2}$ yr, where $\eta \geq 1$ is a gyrofactor, and $V_{1000}$ is the velocity of the reverse shock relative to the unshocked ejecta ahead of it in units of $1000\ km\ s^{-1}$. Therefore, reverse shocks with a typical speed of $\sim 1000\ km\ s^{-1}$ (Laming & Hwang 2003) and a magnetic field of 2 mG can accelerate X-ray-emitting electrons within a timescale of $t_{\text{var}} \sim 4$ yr, provided that the acceleration proceeds close to the Bohm diffusion limit ($\eta \sim 1$).

The observed time variability together with the absence of the Fe-K lines strongly prefer a synchrotron origin of the hard X-ray emission in the selected filaments, providing new evidence of acceleration to multi-TeV energies at the reverse (and transmitted) shocks in ejecta. Although the regions we studied here contain only a portion of the reverse-shocked gas, the bulk of the hard X-rays above 10 keV is also likely of a synchrotron origin. If so, the steepness of the continuum spectrum above 10 keV, $\Gamma \sim 3$ (Favata et al. 1997), indicates that the synchrotron spectrum rolls off at around 1 keV, being consistent with the theory of diffusive shock acceleration (see Uchiyama et al. 2007). The maximum energy of the electrons is thus constrained to be $\sim 10$ TeV. Therefore the TeV $\gamma$-rays measured by HEGRA (Aharonian et al. 2001) and MAGIC (Albert et al. 2007) groups are difficult to be explained by electron bremsstrahlung in the reverse-shocked ejecta, and are likely to be of a hadronic origin.

The interpretation of the X-ray variability has to be critically assessed through future theoretical and observational works. Regardless of what is behind the nonthermal X-ray variability, it offers us a new diagnostic tool to understand particle acceleration in supernova shocks.

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