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Extremely fast acceleration of cosmic rays in a supernova remnant

Yasunobu Uchiyama[1], Felix A. Aharonian[2,3], Takaaki Tanaka[1,4], Tadayuki Takahashi[1] & Yoshitomo Maeda[1]

Galactic cosmic rays (CRs) are widely believed to be accelerated by shock waves associated with the expansion of supernova ejecta into the interstellar medium[1]. A key issue in this long-standing conjecture is a theoretical prediction that the interstellar magnetic field can be substantially amplified at the shock of a young supernova remnant (SNR) through magnetohydrodynamic waves generated by cosmic rays[2,3]. Here we report a discovery of the brightening and decay of X-ray hot spots in the shell of the SNR RX J1713.7−3946 on a one-year timescale. This rapid variability shows that the X-rays are produced by ultrarelativistic electrons through a synchrotron process and that electron acceleration does indeed take place in a strongly magnetized environment, indicating amplification of the magnetic field by a factor of more than 100. The X-ray variability also implies that we have witnessed the ongoing shock-acceleration of electrons in real time. Independently, broadband X-ray spectrometric measurements[4] of RX J1713.7−3946 indicate that electron acceleration proceeds in the most effective ('Bohm-diffusion') regime. Taken together, these two results provide a strong argument for acceleration of protons and nuclei to energies of 1 PeV (10^{15} eV) and beyond in young supernova remnants.

RX J1713.7−3946 (ref. 5) is a unique remnant of a supernova in the sense that its X-ray emission is strongly dominated by a nonthermal component[6–9], which has been presumed to be synchrotron radiation of ultrarelativistic electrons[10,11]. Within the generally accepted theory of diffusive shock acceleration (DSA; reviewed in refs 12, 13), the extension of synchrotron radiation into the X-ray domain requires a high shock speed of about 3,000 km s^{-1} (refs 6, 14). The sub-arcsecond angular resolution of NASA's Chandra X-ray observatory permits the measurement of the shock speed of young, relatively nearby SNRs on the basis of direct observations of proper motions of X-ray-emitting shells. We devised such an 'experiment' by observing the northwest shell of RX J1713.7−3946; this was several years after the initial Chandra observation performed in 2000 (ref. 6).

The new observations with Chandra revealed that the X-ray emission from selected compact regions of the shell seemed variable in flux. The fact that X-ray emission is variable contains unique information about the magnetic field in the particle acceleration region. For a magnetic field typical of the interstellar medium, the acceleration and radiative cooling times of electrons responsible for synchrotron X-ray emission exceed hundreds of years; we therefore 'see' ultrarelativistic electrons, through their nonthermal radiation, accumulated over the history of evolution of the source. The remnant is likely to be about 1,600 years old[15]. The observed rapid variability of X-rays implies that we are dealing with much shorter timescales and provides strong evidence of amplification of the magnetic field around the SNR shell, from the seed (interstellar) value of the order of several μG to the level of mG, as derived below.

We observed the northwest part of RX J1713.7−3946 twice, in July 2005 and May 2006, with the imaging array of the Chandra Advanced CCD Imaging Spectrometer. We also re-analysed the previous Chandra observation of the northwest part in 2000. Figure 1a shows the overall X-ray morphology of the western shell of the SNR, along with sequences of X-ray images of two selected small regions (boxes

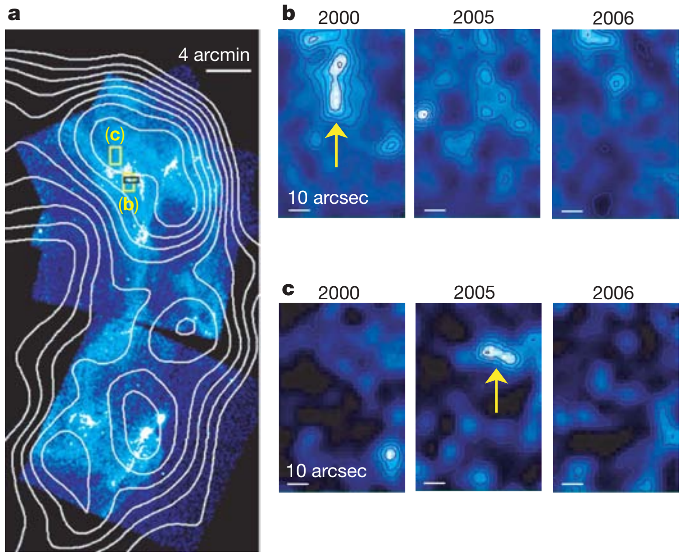

Figure 1 | Chandra X-ray images of the western shell of SNR RX J1713.7−3946. a, A Chandra X-ray mosaic image is overlaid with TeV γ-ray contours from HESS measurements[26]. North is up and east is to the left. With a likely distance to the source $d = 1$ kpc (refs 16, 17), 1 arcmin corresponds to 0.29 pc or 0.95 light years. All Chandra images available are combined into the mosaic image in the energy interval of 1–2.5 keV with a pixel size of 2 arcsec, and smoothed with a gaussian kernel of 8 arcsec to improve the visual appearance. The colour scale is linear in the range $S = (0\text{–}1.2) \times 10^{-7}$ photons $cm^{-2}\,s^{-1}$ per pixel. **b**, A sequence of X-ray observations in July 2000, July 2005 and May 2006 for a small box (labelled b) in **a**. (The black oblong overlapping box b indicates the location in which we compare the cross-sections in Fig. 2.) At each epoch, observations were made for about 30-ks exposure times. The images are produced in the same manner as in **a** and are displayed as surface brightness squared, S^2 (in the range $S = (0\text{–}1.6) \times 10^{-7}$ photons $cm^{-2}\,s^{-1}$ per pixel), to highlight bright regions. A well-defined emission feature with 430 counts ($\sim 10\sigma$ above the surrounding level) in the image from 2000 faded before the year 2005, revealing rapid variability on timescales of years. **c**, Hard-band (3.5–6-keV) images of a box (labelled c) in **a** in terms of S^2 (in the range $S = (0\text{–}0.65) \times 10^{-7}$ photons $cm^{-2}\,s^{-1}$ per pixel). A 'hot spot' (indicated by a yellow arrow) appeared in the 2005 image with 148 counts ($\sim 6\sigma$) and faded before May 2006.

[1]Department of High Energy Astrophysics, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), 3-1-1 Yoshinodai, Sagamihara, Kanagawa, 229-8510, Japan. [2]Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland. [3]Max-Planck-Institut für Kernphysik, PO Box 103980, D69029 Heidelberg, Germany. [4]Stanford Linear Accelerator Center, 2575 Sand Hill Road, M/S 29, Menlo Park, California 94025, USA.

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labelled b and c) at the three epochs. It is clear from Fig. 1b that there is a significant decrease in emissivity in a compact region on a timescale of less than a few years. In Fig. 2 we compare the cross-sections of the X-ray images including this decayed feature in 2000, 2005 and 2006.

Another remarkable feature in the images is that a 'hot spot' 20×5 arcsec^2 in size, seen in 2005 with $\sim 6\sigma$ statistical significance, is not present in the 2000 image, as shown in Fig. 1c. This newly emerged feature disappeared again before May 2006, requiring a decay time of less than one year. We found a dozen additional time-varying compact features of lower significance (2–3σ) from various parts of the northwest shell. They are spatially resolved with Chandra, having a typical apparent width of $\sim$4 arcsec.

The original aim of our imaging analysis was to search for proper motions in the shell structure. By comparing the locations of the outer edge of the shell from the first observation in July 2000 and the latest observation in May 2006, we found that the angular displacement between the two epochs does not exceed 6 arcsec, which implies an upper limit on the shock speed v_s of less than 4,500 km s^{-1} for the adopted distance of 1 kpc (refs 16, 17). This estimate is somewhat less restrictive than originally expected, mainly because of the observed variability of X-ray emission.

The time-variability of X-ray flux on a timescale of Δt can, in principle, be revealed only from a compact region smaller than $c\Delta t$ (c being the speed of light); that is, within an angular size $\theta < c\Delta t/d \approx 1$ arcmin for $\Delta t = 1$ year. This is, however, a necessary but not a sufficient condition. The X-ray variability of compact hot spots in the shell requires sufficiently fast production and losses of parent particles. For any set of reasonable parameters characterizing a SNR (such as total energy budget, gas density, radiation and magnetic fields), only synchrotron radiation of ultrarelativistic electrons accelerated at shock fronts can satisfy these conditions. Other emission models discussed in the literature, such as bremsstrahlung of suprathermal electrons or free–free emission of hot thermal plasma, are now safely rejected. Our results therefore provide the strongest observational proof for the synchrotron origin of X-ray emission from RX J1713.7−3946, and in fact for nonthermal X-ray emission detected so far from any SNR.

The decay of the X-ray brightness can be caused by a decrease in total kinetic energy contained in relativistic electrons (W_e), for example as a result of a decrease in the acceleration efficiency while the electrons continue to radiate, if the synchrotron cooling time is of the order of a year or less. The rapid decrease in emission is unlikely to associate with an escape of electrons; whereas the convective escape is too slow, the fast diffusive escape would contradict the very requirement of effective acceleration. The radiative cooling time of electrons responsible for a synchrotron photon of energy ε is $t_{synch} \approx 1.5\,(B/\text{mG})^{-1.5}\,(\varepsilon/\text{keV})^{-0.5}$ years in a magnetic field of strength B, given that the cooling time of an electron of energy E through synchrotron radiation is $t_{synch} \approx 12\,(B/\text{mG})^{-2}\,(E/\text{TeV})^{-1}$ years, and the average energy of synchrotron photons is $\varepsilon \approx 0.016\,(B/\text{mG})\,(E/\text{TeV})^2$ keV. Therefore, the average magnetic field in the hot spot should be at the level of more than 1 mG to explain the observed timescale of X-ray disappearance.

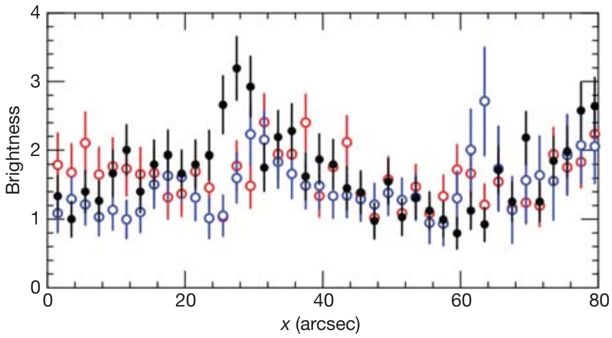

Figure 2 | Cross-sections of the X-ray images at the three epochs. The horizontal (in the east-to-west direction) profiles are extracted from a strip region, indicated as a black oblong overlapping box b in Fig. 1a. Data points are 1–2.5-keV brightness in units of 10^{-6} photons cm^{-2} s^{-1} per bin with a bin size of 2 arcsec with 1σ error bars. They are derived by integrating the surface brightness over a vertical dimension (0.5 arcmin width) for observations in the years 2000 (black), 2005 (red), and 2006 (blue). The brightness peak around $x = 28$ arcsec recorded in 2000 has a clear excess compared with the observations in 2005 and 2006.

The increase in X-ray flux can be caused by an increase in W_e as a result of the boost of the acceleration rate and/or the amplification of the magnetic field. The DSA theory predicts an acceleration time t_{acc} of $\sim 10D(E)v_s^{-2}$ (see, for example, ref. 13), where $D(E) = \eta r_g c/3$ is the diffusion coefficient, $r_g = E/(eB)$ is the gyroradius of an electron with energy E and charge e, and the parameter η characterizes the efficiency of diffusion. The timescale can be rewritten, for electrons emitting synchrotron radiation at energy ε, in the form

$$t_{acc} \approx 1\eta(\varepsilon/\text{keV})^{0.5}(B/\text{mG})^{-1.5}(v_s/3{,}000\ \text{km s}^{-1})^{-2}\ \text{years} \quad (1)$$

For the shock speed $v_s < 4{,}500$ km s^{-1}, as derived in this work, the acceleration time of electrons responsible for X-rays significantly exceeds the timescales of the observed X-ray variability unless the magnetic field upstream is of order 1 mG and particle acceleration proceeds in the maximum effective (Bohm-diffusion) regime with $\eta \approx 1$. Note that equation (1) corresponds to the parallel shock acceleration, the most feasible and generally accepted version of DSA. It has been suggested[18], however, that in strongly oblique shocks the rate of the energy gain of particles could be higher. In addition, it has recently been argued[19] that nonlinear shock-acceleration can proceed beyond the Bohm limit. If so, this would relax somewhat the above requirement to the strength of the magnetic field. In contrast, the estimate of the magnetic field derived from the synchrotron cooling time of electrons does not depend on the electron acceleration mechanism, and therefore the requirement of $B > 1$ mG remains rather robust.

The mG-scale magnetic field inferred from the X-ray variability is evidence in support of the substantial amplification of the magnetic field upstream of the shock from the interstellar value. This is a key condition for the acceleration of protons and nuclei to energies beyond the so-called Lagage–Cesarsky limit around 100 TeV (ref. 20). Recent theoretical studies[2,3] suggest that CR-excited magnetohydrodynamic waves are indeed able, at least in principle, to amplify the magnetic field by orders of magnitude from its initial seed value, although many complex, highly nonlinear microscopic processes remain to be explored.

The strength of the magnetic field can be estimated indirectly from the width of X-ray filaments if one interprets the origin of these thin structures in terms of diffusion and synchrotron cooling of electrons[21–25]. In particular, for RX J1713.7−3946, this method gives lower limits on the field strength in a range of 0.07–0.25 mG (ref. 25). The variability of the compact hot spots is probably a manifestation of the strongest amplification of the magnetic field, whereas more diffuse regions in the shell would have somewhat weaker magnetic fields.

The broadband X-ray spectroscopy obtained recently by the Suzaku satellite (see Fig. 3) provides independent evidence of very effective acceleration of particles in the shell of RX J1713.7−3946. The measured energy spectrum agrees well with theoretical expectations for the spatially integrated synchrotron spectrum[14] described by a single parameter $\varepsilon_0 = 0.55\eta^{-1}(v_s/3{,}000\ \text{km s}^{-1})^2$ keV. The Suzaku spectral data from 0.4 to 40 keV can be well fitted by the theoretical spectrum with $\varepsilon_0 = 0.55$–0.65 keV, which implies that acceleration should proceed close to the extreme Bohm diffusion limit, $\eta \approx 1$, given the constraint of $v_s < 4{,}500$ km s^{-1}.

Now we can estimate the acceleration time of cosmic-ray protons with energy E at the present epoch merely on the basis of the X-ray

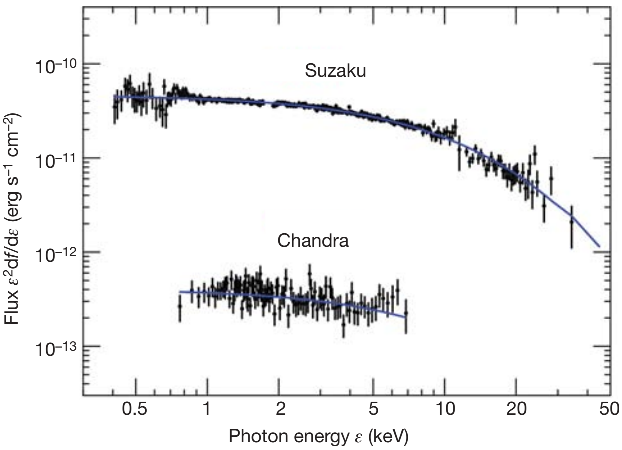

Figure 3 | Energy spectrum of X-ray emission of SNR RX J1713.7−3946. **Broadband spectroscopic measurements were made with the Suzaku X-ray satellite in September 2005 (ref. 4). Error bars are 1σ. The Suzaku X-ray spectrum from 0.4 to 40 keV was obtained after integration over the southwest shell of the remnant. In addition, a Chandra X-ray spectrum taken in July 2000 is extracted from the filamentary feature in box b of Fig. 1a. Here we fit the spectra with the theoretical spectrum (solid blue lines) of synchrotron radiation from the shock-accelerated electrons, attenuated by the intervening gas with hydrogen column density N_{H}. The synchrotron spectrum predicted by classical DSA theory has the form $\varepsilon^2 \mathrm{d}f/\mathrm{d}\varepsilon \propto [1 + 0.46(\varepsilon/\varepsilon_0)^{0.6}]^{2.29} \exp[-(\varepsilon/\varepsilon_0)^{0.5}]$, with $\varepsilon_0 = 0.55\eta^{-1}(v_s/3{,}000\ \mathrm{km\ s^{-1}})^2$ keV (ref. 14). The flux points are reconstructed with the best-fit function, with correction for the interstellar absorption. The Suzaku wide-band spectrum has a convex curve, rolling off above $\sim$5 keV. We obtain $\varepsilon_0 = 0.7 \pm 0.2$ keV, with $N_{\mathrm{H}} = (0.79 \pm 0.05) \times 10^{22}\ \mathrm{cm^{-2}}$, for the Chandra spectrum, whereas $\varepsilon_0 = 0.61 \pm 0.05$ keV, with $N_{\mathrm{H}} = (0.77 \pm 0.02) \times 10^{22}\ \mathrm{cm^{-2}}$, for the Suzaku data. The best-fit values of ε_0 yield $\eta \approx 1(v_s/3{,}000\ \mathrm{km\ s^{-1}})^{-2}$. We find that a good fit to the X-ray spectrum can also be formally obtained with the so-called SRCUT model[10], but only below 10 keV. The limited angular resolution of Suzaku unfortunately does not allow spectral measurements of selected compact regions. However, similar shapes of the Chandra spectra extracted from various regions[6] suggest that the Suzaku spectrum generally also characterizes the broadband X-ray spectra of small-scale regions.**

measurements, $t_{\mathrm{acc}} \approx 0.1(B/\mathrm{mG})^{-1}(E/\mathrm{TeV})$ years, assuming that the acceleration times of protons and electrons with the same energy are equal. Whereas the maximum energy of electrons is limited by synchrotron losses below $\sim$10 TeV, protons and nuclei can be accelerated, over time ΔT, to $E \approx 1(B/\mathrm{mG})(\Delta T/100\ \mathrm{years})$ PeV. This is also supported by recent γ-ray observations of RX J1713.7−3946, because the observed spectrum extending to 100 TeV can be naturally explained by hadronic proton–proton interactions[26]. Note that the TeV γ-rays cannot be accounted for by inverse Compton scattering of ultrarelativistic electrons. Indeed, the simple one-zone inverse Compton model, which requires an average magnetic field of $\sim$10 μG (ref. 26), is immediately excluded because of the mG-scale magnetic field derived above. The good spatial correlation of TeV γ-ray and X-ray fluxes as seen in Fig. 1a does not leave room for speculations about a more sophisticated two-zone model. The keV–TeV correlation is in fact better explained by the hadronic model of γ-rays, assuming that protons and electrons are effectively confined in and interacting with the same shocked regions of the SNR shell.

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Author Contributions Y.U. performed analysis of data obtained with the Chandra observations. F.A. investigated theoretical aspects of this work. Y.U. and F.A. jointly wrote the paper. T. Tanaka performed analysis of data obtained with the Suzaku observations. Y.M. checked the analysis of the Chandra data. T. Takahashi wrote a proposal requesting the Suzaku observations. All authors discussed the results and commented on the manuscript.