Flat Spectrum X-ray Emission from the Direction of a Molecular Cloud Associated with SNR RX J1713.7−3946

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Abstract

We report on the discovery of a diffuse X-ray source with ASCA, presumably associated with a molecular cloud in the vicinity of the supernova remnant RX J1713.7−3946. The energy spectrum (1–10 keV) of the hard X-ray source shows a flat continuum, which is described by a power-law with a photon index of $\Gamma = 1.0^{+0.4}_{-0.3}$. We argue that this unusually flat spectrum can be best interpreted in terms of characteristic bremsstrahlung emission from the loss-flattened distribution of either sub-relativistic protons or mildly relativistic electrons. The strong shock of RX J1713.7−3946, which is likely to interact with the molecular cloud, as evidenced by CO-line observations, seems to be a natural site of acceleration of such nonthermal particles. The observed luminosity of $L_X = 1.7 \times 10^{35}$ erg s$^{-1}$ (for a distance of 6 kpc) seems to require a huge kinetic energy of about $10^{39}$ erg in the form of nonthermal particles to illuminate the cloud. The shock-acceleration at RX J1713.7−3946 can barely satisfy this energetic requirement, unless (i) the source is located much closer than the preferred distance of 6 kpc and/or (ii) the mechanical energy of the supernova explosion essentially exceeds $10^{51}$ erg. Another possibility would be that an essential part of the lost energy due to the ionization and heating of gas, is somehow converted to plasma waves, which return this energy to nonthermal particles through their turbulent reacceleration on the plasma waves.

Key words: acceleration of particles — radiation mechanisms: non-thermal — ISM: cosmic rays — ISM: supernova remnants — X-rays: individual (RX J1713.7−3946)

1. Introduction

Supernova remnants (SNRs) are commonly believed to be major sites for the production of Galactic cosmic rays. The diffusive shock acceleration mechanism naturally accounts for the hard power-law production spectra of cosmic rays in their sources, but, as long as the particle injection rate remains an unsolved problem, the theory does not tell us conclusively what fraction of the initial kinetic energy of an explosion can be transferred to cosmic rays (see e.g. the recent review by Malkov, Drury 2001). Therefore, it is extremely important to derive the total energy contained in subrelativistic and relativistic particles from observations of the relevant components of nonthermal electromagnetic radiation.

Radio synchrotron emission provides information about GeV electrons in most shell-type SNRs. Synchrotron X-ray emission recently discovered in SN 1006 (Koyama et al. 1995) and some other shell-type SNRs indicates that the electron acceleration continues effectively up to multi-TeV energies. It is believed, however, that the accelerated protons constitute the major fraction of nonthermal energy to which the mechanical energy of a supernova explosion is transferred through shock acceleration. The best way to explore the proton component of accelerated particles in SNRs is the detection of gamma-rays by the decay of $\pi^0$ mesons produced in collisions between cosmic-ray protons and ambient matter (Drury, et al. 1994; Naito, Takahara 1994). The detection of gamma-rays of hadronic origin from SNRs by current and planned space- and ground-based instruments requires high-density environments in or close to the particle-acceleration sites. Large molecular clouds interacting with shells of SNRs may act as effective gas targets for the production of $\pi^0$ mesons and their subsequent decay to high-energy $\gamma$-rays (Aharonian, et al. 1994). It has recently been claimed (Butt et al. 2001) that there exists a compelling positional association of the unidentified $\gamma$-ray source 3EG J1714−3857 with a dense molecular cloud (cloud A) overtaken, most probably, by the shock front of the SNR RX J1713.7−3946 (G 347.3−0.5). Moreover, it has been argued that the TeV gamma-rays from this SNR detected by the CANGAROO collaboration are also the result of interactions of accelerated protons with nearby dense gas targets (Enomoto et al. 2002), though Reimer and Poli (2002) claimed that this interpretation seems to be inconsistent with EGRET observations of this region.

The flux of the subrelativistic component of the accelerating protons is generally inconclusive both on observational and theoretical grounds, but it is quite possible...
that this component dominates the total energetics of nonthermal particles. Unfortunately, subrelativistic protons arriving at the Earth are not a representative sample of the cosmic-ray flux in the Milky Way owing to the effect of solar modulation. Ionization losses of these particles play an important role in heating both diffuse neutral gas and molecular clouds, and in generating free electrons in molecular clouds, which are crucial for interstellar chemistry. It is therefore of great importance to measure the energy released in the form of subrelativistic particles by cosmic-ray accelerators.

The ideal diagnostic tool to probe subrelativistic cosmic rays is the nuclear prompt $\gamma$-ray line emission at MeV energies (Ramaty, Lingenfelter 1979). However, conservative estimates show that the fluxes of even most prominent $\gamma$-ray lines are only marginally detectable because of limited sensitivities of gamma-ray instruments in the MeV band. On the other hand, as we discuss below, the search for the sites of concentrated subrelativistic protons using bremsstrahlung X-rays could be very promising with the help of superior sensitivities of current X-ray detectors, even though only a small fraction ($\sim 10^{-5}$) of the nonthermal energy of subrelativistic protons and electrons is radiated away in the form of bremsstrahlung X-rays. Remarkably, if the subrelativistic cosmic rays reside in a dense gas environment, the ionization losses would result in a significant flattening of the low-energy spectra, and thus leading to the characteristic $1/\varepsilon$ type bremsstrahlung X-ray spectrum (Uchiyama et al. 2002). Such an unusually hard X-ray spectrum may serve as a distinct signature of nonthermal bremsstrahlung origin of X-ray emission.

In our previous paper (Uchiyama et al. 2002) we reported on the detection of hard X-rays from a localized region in the SNR $\gamma$ Cygni, which we attributed to $1/\varepsilon$ bremsstrahlung from the loss-flattened electron distribution. In this paper we present a more pronounced example of such hard X-radiation arriving from a massive cloud in the vicinity of SNR RX J1713.7–3946.

2. SNR RX J1713.7–3946
2.1. Basic Information from Previous Studies

The shell-type SNR RX J1713.7–3946 (G 347.3−0.5), which has an angular radius of about 40′, was first discovered during the ROSAT All-Sky Survey (Pfeffermann, Aschenbach 1996). The detection of synchrotron X-ray emission with ASCA (Koyama et al. 1997; Slane et al. 1999) revealed that the remnant’s shell is a presently operating source of multi-TeV electrons, which are responsible for the synchrotron X-rays. Moreover, the TeV $\gamma$-rays detected by the CANGAROO collaboration from this supernova remnant (Muraishi et al. 2000; Enomoto et al. 2002) provide direct evidence of the acceleration of particles – electrons and/or protons – to energies well beyond 10 TeV. This SNR is very faint at radio wavelengths. Based on a lack of thermal X-ray emission, the supernova shock is considered to be expanding in a low-density environment, such as a stellar-wind cavity (Slane et al. 1999).

The distance $d$, age $\tau$, and the explosion energy $E_{51} = E/10^{51}$ erg are three important parameters for understanding the origin of nonthermal radiation components. At the perimeter of RX J1713.7–3946, there is a dense ($n \sim 1 \times 10^{3}$ cm$^{-3}$) molecular cloud (cloud A) that seems to have a very high ratio of two rotational transition lines of CO molecules, CO($J=2–1$)/CO($J=1–0$). This suggests an interaction between cloud A and the SNR RX J1713.7−3946 (Slane et al. 1999; Butt et al. 2001). The distance to cloud A ($V_{LSR} = -94$ km s$^{-1}$) was kinematically estimated to be $6.3 \pm 0.4$ kpc by using the standard Galactic rotation curve (Slane et al. 1999). Thus, if the molecular cloud and the supernova remnant are indeed physically associated, the distance to RX J1713.7−3946 could be significantly larger than the original estimate of about 1 kpc based on an absorbing column-density value (Koyama et al. 1997). For the preferred distance to the source of about 6 kpc, a reasonable set of the age and the explosion energy of RX J1713.7−3946 is in the ranges 1700–4000 yr and $E_{51} = 2.2–1.7$ (Slane et al. 1999).

However, a different solution of a distance $d = 2$ kpc, with the remnant’s age of 2100–3400 yr and the SN explosion energy of $E_{51} = 1.4–2.2$, cannot be ruled out. The smaller distance and correspondingly younger remnant agree better with the hypothesis of Wang et al. (1997) who argued that RX J1713.7−3946 could be a likely counterpart of the guest star of 393 a.d. in the constellation Scorpius.

2.2. ASCA Analysis

The SNR RX J1713.7−3946 was partially observed with the ASCA satellite on 1996 September, and most of the remnant was covered on 1997 March. The data were screened by standard procedures, except that strict risetime screening was not applied to the data taken on 1997 March. Below we present the results from the Gas Imaging Spectrometer (GIS) by adding two identical detectors (GIS 2 and GIS 3).

Figure 1 shows the X-ray images of the SNR RX J1713.7−3946 in the soft 1–3 keV and hard 5–10 keV energy bands. After subtracting the instrumental background and correcting vignetting effect, images are smoothed with a Gaussian of standard deviation of $80′′$. We thus refer to this source as AX J1714.1−3912. The count rate in the 5–10 keV band of AX J1714.1−3912 is $0.029$ c s$^{-1}$, which corresponds to a $34 \sigma$ statistical significance in excess of the background in this region. The total number of source photons detected in the 1–10 keV band is derived to be 3340. Unfortunately, the source lies very near to the edge
of the observed field. It is therefore difficult to determine any extent of the source, which is distorted by the off-axis broad point spread function of the telescope.

The X-ray spectrum of each region (1–4) was derived by subtracting the contributions from the Galactic diffuse emission taken from a nearby field, and then fitted with a photoelectric-absorbed power-law model, described as

$$F(\varepsilon) \sim \varepsilon^{-\Gamma} \exp[-N_H \sigma(\varepsilon)],$$

where $\Gamma$ is a photon index, $\sigma(\varepsilon)$ is the photoelectric cross-section, and $N_H$ is the equivalent hydrogen column density. All four spectra were well-fitted by these simple models. The best-fit parameters and their 90% confidence limits are summarized in table 1. The energy spectra and the best-fit models of region 1 (i.e., AX J1714.1–3912) and region 2 are shown in figure 2. The power-law indices in region 2–4, $\Gamma = 2.1–2.3$, are consistent with previous measurements and are best explained by synchrotron radiation from ultrarelativistic electrons. We found that the spectrum of AX J1714.1–3912 is best fitted by an extremely flat power-law model with $\Gamma = 1.0^{+0.4}_{-0.3}$. Within the statistical uncertainties, the absorbing column density for region 1 agrees with that obtained for region 2–4. Attempts at fitting a thermal-bremsstrahlung model to the region 1 spectrum gave a lower-limit temperature of 35 keV (90% confidence), which is unreasonably high for SNRs.

3. Discussion

3.1. On the Origin of Flat X-Ray Emission

We have discovered a new X-ray source, AX J1714.1–3912, with an extent of $\sim 10^\prime$, characterized by an extremely flat power-law with $\Gamma = 1.0^{+0.4}_{-0.3}$. The luminosity of the source is estimated to be

$$L_X = 1.7 \times 10^{35} d_8^2 \text{ erg s}^{-1},$$

where $d_8$ is the distance to the source normalized to 6 kpc. Since the luminosity increases linearly with a high-energy cutoff for the $\varepsilon^{-\Gamma}$ type spectrum, the above estimate should be considered as a lower limit for the luminosity. It cannot be the radiation of thermal gas, unless we assume an extremely hot optically thin plasma with a temperature significantly exceeding 10 keV. Since the formation of such a thermal source seems to be quite problematic, given its extended character, below we assume that the X-radiation has a nonthermal origin. AX J1714.1–3912 has a good spatial association with cloud A (see figure 1). In the following discussion, therefore, we assume that the X-ray emission actually comes from cloud A. If so, this would be a new striking nonthermal phenomenon in molecular clouds.

Nonthermal particles that are illuminating cloud A in the X-ray band could be supplied by either internal or external accelerators. A potential candidate for an external accelerator is the strong shock of SNR RX J1713.7–3946, which is likely to interact with cloud A, as evidenced by a very high ratio of CO(J=2–1)/CO(J=1–0) (Butt et al. 2001). The particles can be accelerated in the shell of RX J1713.7–3946 and afterwards enter cloud A, given that the shell is a certain site of particle acceleration, which follows from synchrotron X-ray emissions. It is possible that particle acceleration also takes place at the secondary shocks inside (or in the vicinity of) cloud A initiated by the main shock of the SNR. Finally, if there is no physical link between cloud A and SNR RX J1713.7–3946, this would imply the existence of unseen internal accelerators inside the molecular cloud. Although we cannot exclude any of these possibilities, the preferred option seems to be the “cloud interacting with SNR” scenario.

Formally, there are also several options for the nonthermal X-ray production mechanisms: synchrotron radiation, inverse Compton (IC) scattering, and electron and/or proton bremsstrahlung. However, here more definite conclusions can be drawn.

3.2. Difficulties in Synchrotron and IC Processes

Synchrotron X-ray emission by multi-TeV electrons could not explain the flat X-ray spectrum. Because of the fast synchrotron cooling on a timescale of $\tau_{\text{syn}} \sim 150 (\varepsilon/5 \text{ keV})^{-1/2} \text{ yr}$ (for a magnetic field of 25 $\mu$G typical in molecular clouds), the photon index of the synchrotron spectrum at X-ray energies becomes $\Gamma = \alpha_e/2 + 1$, where $\alpha_e \sim 2–2.2$ is the electron acceleration index. Thus, the differential spectrum of synchrotron X-radiation cannot be flatter than $\varepsilon^{-2}$. Note that the power-law fits of the X-ray spectra of regions 2–4 ($\Gamma = 2.1–2.3$) agree with the synchrotron origin of X-rays from these regions.

Inverse Compton scattering is precluded by low brightness of synchrotron radio emission. Relatively low-energy (GeV) electrons that produce X-rays via scattering off the cosmic microwave background photons, also emit synchrotron radiation at radio frequencies. Thus, assuming that the X-ray flux is due to IC scattering, we can calculate the radio flux density of the associated synchrotron emission. For a magnetic field of 25 $\mu$G the latter is expected at a level of $10^4$ Jy at 843 MHz, which is higher, by three orders of magnitudes, than the upper limit on the radio flux from the direction of cloud A (Slane et al. 1999). Therefore, we can safely exclude the IC origin of the observed X-radiation.

3.3. 1/$\varepsilon$ Bremsstrahlung

X-rays can be produced through the bremsstrahlung of nonthermal electrons and/or protons interacting with...
the cloud gas. The energy distribution, for either accelerated protons or electrons within the cloud, is characterized by the position of the break energy, $E_{\text{br}}$, which is set by equating the lifetime against the ionization losses and the age of the accelerator, $\tau_{\text{ion}} = \tau_{\text{age}}$. At energies below $E_{\text{br}}$, for which $\tau_{\text{ion}} < \tau_{\text{age}}$, the particle distribution becomes “loss-flattened” due to ionization losses (Uchiyama et al. 2002). As a result, the bremsstrahlung spectrum obey a characteristic energy distribution close to $I(\varepsilon) \propto 1/\varepsilon$, provided that the energy spectrum of the subrelativistic particles becomes harder than $E^{-1/2}$. Almost independent of the details of the acceleration spectrum, this criterion could be satisfied by the loss-flattened distribution below $E_{\text{br}}$, which is controlled by the density of the cloud $n$ and the source age $\tau_{\text{age}}$. For $n = 10^3 \text{ cm}^{-3}$ and $\tau_{\text{age}} = 10^3$ yr, the break appears at $E_{p,\text{br}} \simeq 20 \text{ MeV}$ in the proton distribution, and correspondingly at $E_{e,\text{br}} = (m_e/m_p)E_{p,\text{br}} \simeq 11 \text{ keV}$ in the proton bremsstrahlung spectrum. On the other hand, the breaks are $E_{e,\text{br}} = \varepsilon_{e,\text{br}} \simeq 7 \text{ MeV}$ for electrons. At photon energies anywhere below $\varepsilon_{e,\text{br}}$, the characteristic $1/\varepsilon$ power-law is predicted. Note that the $1/\varepsilon$ bremsstrahlung photons below $\varepsilon_{e,\text{br}}$ are produced predominantly by particles in a narrow energy interval around $E_{\text{br}}$. The spectral shape of the flat X-ray spectrum of AX J1714.1−3912 agrees perfectly with the $1/\varepsilon$ emission of either proton bremsstrahlung (PB) or electron bremsstrahlung (EB) from the loss-flattened distribution.

Whereas the PB and EB mechanisms are expected to give rise to the same $1/\varepsilon$ X-ray spectrum, the PB luminosity peaks at (hard) X-rays and the EB peaks at gamma-rays for typical parameters. In the case of the $1/\varepsilon$ EB emission, the photon flux per each logarithmic interval in photon energy anywhere up to $\varepsilon_{e,\text{br}} \sim 7 \text{ MeV}$ is constant. Then, the observed X-ray flux of $4 \times 10^{-3}$ photon cm$^{-2}$ s$^{-1}$ in the 1–10 keV band implies that the 1–10 MeV flux should be comparable to the Crab. This is inconsistent with non-detection by the COMPTEL instrument (Schönhälfker et al. 1996) onboard the Compton Gamma Ray Observatory. Moreover, unless we introduce a sharp cutoff in the electron distribution at an energy of around 100 MeV, the EB model overshoots the $\gamma$-ray flux reported by the EGRET instrument. Therefore, we may conclude that the gamma-ray data favor proton bremsstrahlung, rather than the electron bremsstrahlung scenario.

3.4. Energetics Requirement of $1/\varepsilon$ Bremsstrahlung

The X-ray luminosity of the $1/\varepsilon$ bremsstrahlung emission of either protons or electrons can be estimated as

$$L_X \sim \eta_{p,e} \left( \frac{W_{\text{br}}}{\tau_{\text{age}}} \right),$$

(1)

where $W$ is the total amount of kinetic energy contained in X-ray emitting particles, $\tau_{\text{age}}$ is the age of the source (accelerator), and $\eta = \tau_{\text{ion}}/\tau_{\text{rem}}$. Here, we take into account that the bulk of X-rays are produced by particles from the break region, thus $\tau_{\text{age}} = \tau_{\text{ion}}$. For the parameters chosen above, $\eta_p = 3 \times 10^{-5}$ and $\eta_e = 9 \times 10^{-5}$. These factors demonstrate the low efficiency of the bremsstrahlung mechanism relative to the ionization losses, implying a huge, $W_p = 5.6 \times 10^{39} d_6^4 \text{ erg s}^{-1}$ and $W_e = 1.9 \times 10^{39} d_6^4 \text{ erg s}^{-1}$, injection power in protons and electrons, respectively. Correspondingly, the total amounts of energy released during operation of the accelerator are $W_{\text{br}}^{\text{sub}} = 1.8 \times 10^{50} d_6^2 (\tau_{\text{age}}/10^3 \text{ yr})$ erg and $W_e = 7.2 \times 10^{49} d_6^2 (\tau_{\text{age}}/10^3 \text{ yr})$ erg.

If the particles are accelerated in the shell of SNR RX J1713.7−3946, and only a relatively small (10% or so) fraction of these particles enter cloud A, the total kinetic energy, which is transferred to subrelativistic protons, should be at least $10^{51}$ erg; the electron bremsstrahlung model alleviates the total energy by a factor of about 3. Given the limited energy budget of a supernova shock of about $10^{51}$ erg, we face a serious problem to support the required X-ray luminosity, unless the system is closer to the Earth than estimated by the radial velocity of cloud A. For example, a distance of 2 kpc would reduce the energy requirement to a quite comfortable level of $\sim 2 \times 10^{50}$ erg. Several other scenarios may be invoked to overcome the energy budget problem. The simplest assumption would be that the explosion energy significantly exceeds $10^{51}$ erg, and that more than 10% of this energy is released in the form of subrelativistic particles. It is also possible that the nonthermal particles are accelerated inside the cloud, e.g. by the shock initiated at the collision of the blast wave of RX J1713.7−3946 with cloud A (Bykov et al. 2000). Finally, we may speculate that the essential part of the energy which goes into the ionization and heating of gas, and also the excitation of plasma waves, is returned to subrelativistic protons through acceleration on these plasma waves. Apparently, all of these assumptions need detailed quantitative studies.

AX J1714.1−3912 and cloud A are located within the error box of the unidentified $\gamma$-ray source 3EG J1714−3857 (Hartman et al. 1999). The GeV $\gamma$-ray flux may be explained by $\pi^0$ gamma-rays by collisions between the shock-accelerated protons and cloud A. Butt et al. (2001) argued that an electron-bremsstrahlung origin for the GeV flux is less likely because of the faint synchrotron radio emission of cloud A. The total energy liberated in $\gamma$-rays through the decay of neutral pions is roughly estimated to be $L_\gamma \sim (1/3) \sigma_{p\pi} n c W_p^{\text{rel}}$ where $\sigma_{p\pi} \simeq 30 \text{ mb}$ is the proton–proton inelastic cross-section, and $W_p^{\text{rel}}$ is the energy content in GeV protons, within cloud A. The EGRET luminosity, $L_\gamma = 6.5 \times 10^{35} d_6^4 \text{ erg s}^{-1}$, corresponds to $W_p^{\text{rel}} = 2.2 \times 10^{18} d_6^2 \left( n/10^3 \text{ cm}^{-3} \right)^{-1} \text{ erg}$. Thus, with the proton-bremsstrahlung model for AX J1714.1−3912, the energy content in subrelativistic protons far exceeds that in relativistic protons, $W_p^{\text{rel}} \lesssim 80 W_p^{\text{rel}}$. In this case, it would appear that the acceleration/injection mechanisms allow a small fraction of protons to be accelerated to relativistic energies. Another possibility could be that the bulk of accelerated relativistic protons have already diffused away, while the subrelativistic protons are still being captured within the molecular cloud.

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Fig. 1. X-ray surface brightness (color map linearly spaced from black to white) of the SNR RX J1713.7–3946 in (a) 1–3 keV and (b) 5–10 keV energy bands obtained with the ASCA GIS detectors. Right ascension and declination are in the J2000 coordinate system. The white thick line represents the Galactic plane. A transient X-ray source (Koyama et al. 1997) is blanked out [a white cross in (b)]. Depicted are the 68% confidence error contour of the EGRET unidentified source 3EG J1714–3857 (Butt et al. 2001), and an approximate outline of cloud A based on the CO(J=1–0) intensity (Bronfman et al. 1989).
Fig. 2. Unfolded X-ray spectra of region 1 (AX J1714.1−3912) and region 2 measured by the ASCA GIS detectors. The solid lines are the best-fit power-law models, taking account of the photoelectric absorption at lower energies (see table 1), while the dashed lines are absorption-corrected power-law spectra. For illustrative purposes, we show the X-ray spectra of region 1 being derived by using an alternative background field (open circles).