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EVIDENCE FOR COSMIC-RAY ACCELERATION IN SUPERNOVA REMNANTS FROM X-RAY OBSERVATIONS

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ABSTRACT

Spatially-resolved X-ray spectroscopic observations over the past several years have led to the discovery of non-thermal X-ray emission arising in the shells of most young Galactic supernova remnants, most notably SN 1006 and Cas A. In addition, the X-ray emission from the shells of a few newly-discovered supernova remnants is dominated by a non-thermal component. This emission is thought to be synchrotron emission from electrons shock acclerated to hundreds of TeV, and thus represents strong evidence that cosmic rays are accelerated in SNR shocks. The inferences made using the X-ray observations are corroborated by the detection of TeV γ-rays from two of these remnants. We review the status of the X-ray observations and describe how they can be used to provide insight into the shock-acceleration process.

INTRODUCTION

It has been postulated for many years that cosmic rays with energy as high as the ~3,000 TeV spectral turnover (or "knee") are produced by diffusive shock acceleration in Galactic supernova remnants (SNR's). The acceleration sites cannot be observed directly because the intervening Galactic magnetic fields curve the trajectories of these energetic particles. Detection of synchrotron emission from SNR shells in the radio band verify that electrons with energies up to the GeV range are accelerated there. Until recently, however, it has not been possible to search for evidence of particles with energy closer to the knee. Throughout the infrared, visible, and ultraviolet bands, the surface brightness of the synchrotron spectrum extrapolated from the radio is substantially lower than that of thermal emission from shock-heated gas. If the synchrotron spectrum continues unaltered through the X-ray band, it would be the dominant emission component. The spectral slope steepens in the X-ray band, however, so even there the synchrotron emission is dominated by the thermal X-rays from gas shock-heated to temperatures of $\sim 10^7$ K. Only above ~5 keV, where this thermal emission falls off, might it be possible to detect synchrotron emission in the form of a hard continuum component, but only if electrons are accelerated to sufficiently high energy, on the order of 100 TeV.

The broad bandpass, high sensitivity and moderate resolution spectral capabilities of the X-ray observatories launched in the mid 1990's, ASCA and RXTE, led to a breakthrough in our ability to detect evidence for highly relativistic particles in SNR shells. The first breakthrough came from the ASCA observations of the supernova remnant SN 1006. This remnant was known to have a featureless integrated spectrum above 1 keV. It was possible to construct models of the spectrum by extreme departure of shock heated gas of a particular composition from ionization equilibrium (Hamilton, Sarazin & Szymkowiak 1986). ASCA provided the first broad-band, spatially-resolved spectrum, which revealed that only the bright northeast and southwest limbs have a featureless spectrum, and that the emission from the remainder of the remnant is line-rich thermal emission from gas enriched by supernova ejecta. The most plausible origin of the emission from the bright limbs is synchrotron radiation from electrons with energies up to ~200 TeV. As acceleration processes at these highly relativistic energies make no distinction between positively and negatively charged particles,

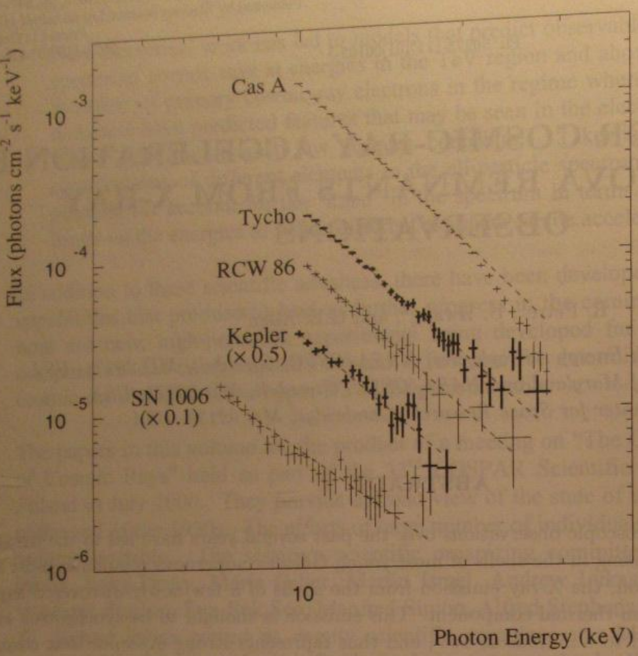

Fig. 1. Spectra of hard X-ray components in five supernova remnants, as observed by RXTE. Each spectrum is characterized by a power law with spectral index $\alpha \sim 2$, and is probably produced by synchrotron emission by electrons shock-accelerated to TeV energy.

we infer that protons and nuclei are being accelerated to these energies as well, and therefore SN 1006 is the first identified cosmic ray source (Koyama et al. 1995). Theoretical models support this conclusion (e.g. Reynolds 1996), or show that alternative interpretations fail (e.g., Laming 1998). Moreover, this conclusion has been dramatically confirmed by the subsequent detection of TeV γ-rays from SN 1006, which arise from Compton scattering of cosmic microwave background photons off the TeV electrons (Tanimori et al. 1998).

The SN 1006 discovery prompted a flurry of searches for synchrotron components in other remnants. Components have been found primarily via systematic searches through archival ASCA or RXTE data (e.g., Keohane 1998; Tomida 2000), but some serendipitously discovered remnants also turned out to have continuum-dominated spectra (Koyama et al. 1997). It is now generally the case that X-ray spectral analysis of SNR's usually includes a search for a hard, nonthermal component. The presence of a hard X-ray continuum component does not automatically mean that another site of cosmic ray acceleration has been identified: other mechanisms, both thermal and nonthermal, can produce hard components (e.g., Asvarov et al. 1990, Laming 1998, Tatischeff et al. 1998), and care must be taken in each instance to rule out these

CURRENT STATUS OF OBSERVATIONS

In Table 1 we list remnants for which nonthermal shell emission components have been reported. While they range in age from 350 yr to 15,000 yr, most are young (~10^3 yr). Those in bold face are the ones for which we are fairly certain the nonthermal component is contributed by synchrotron emission from TeV electrons. The list contains virtually all known shell-like Galactic SNR's younger than ~1,500 years.

In Figure 1 we show the spectra at energies above 5 keV for five of the remnants listed in Table 1, as observed by RXTE. In each case, the spectrum is represented by a power law or broken power law, with spectral index of $\alpha \sim 2$. This is steeper than the $\alpha \sim 1$ generally observed from synchrotron radiation as

Table 1. Galactic SNR's with Hard, Nonthermal X-Ray Spectral Components

Object	Age (ky)	R/X Match?	Low L_R	Type	Result	Reference
Cas A	0.3	Y	N?	II	Synchrotron tail extends to $\geq$ 100 keV	Allen et al. 1997
Kepler	0.4	Y	N	II?	$\alpha \sim 2.5$	Decourchelle et al. 2000
Tycho	0.4	N	N	Ia	Tail with $\alpha \sim 2$ extends $\geq$ 20 keV	Allen et al. 1999
G266.3-1.2	$\sim$1	?	Y	II?	RXTE shows $\alpha \sim 2$; low n medium	Slane et al. 1999
SN 1006	1.0	Y	Y	Ia	Obvious nonthermal shell; TeV γ-rays	Koyama et al. 1995
W49B	1-3	Y	N	?	Hard X-ray continuum has $\alpha \sim \alpha_{1006}$	Keohane 1998
RCW 86	$\sim$2	N	N	II?	Tail has $\alpha \sim 2$ extending $\geq$ 20 keV	Borkowski et al. 2000
G347.5-0.5	$\sim$4	?	Y	II?	Nonthermal spectrum; $\alpha \sim$1.5; low ρ	Koyama et al. 1997
G156.2+5.7	15	Y	Y	II?	ASCA, Ginga show $\alpha \sim 2$; low ρ	Tomida 2000
IC 443	1-4	N	N	II	NT flux from enhanced acceleration due to strong shock/cloud collision	Keohane et al. 1997
W50	5-10	N	N	II	NT flux from electrons accelerated in jet/cloud collision	Safi-Harb & Petre 1999

ated with pulsars, and flatter than the $\alpha \geq 5$ that characterizes thermal emission that might be expected from these remnants in the 5-15 keV band. For three of these remnants, SN 1006, Cas A, and RCW 86, there is morphological evidence that this hard component is produced by shock-accelerated electrons.

In three of these remnants, SN 1006, G266.3-1.2, and G347.5-0.5, the nonthermal X-rays dominate. For G347.5-0.5 there is also a report of a TeV γ-ray detection (Muraishi et al. 2000). These SNR as a group with the addition of G156.2+5.7) share another important property: they have low radio surface brightness. The low radio surface brightness and lack of strong thermal X-rays could both be the consequence of SNR expansion into a very low density ISM. In such a medium, a remnant decelerate more slowly, enhancing shock acceleration (which depends strongly on shock velocity). At the same time, there is insufficient material to produce a strong reverse shock, which in turn substantially reduces the thermal X-ray flux.

CHANDRA RESULTS

The recent launch of the *Chandra* and XMM/*Newton* observatories provide us with powerful new tools for identifying possible sites of cosmic-ray acceleration in SNR's. XMM/*Newton* offers broad band, high throughput imaging that will allow us to observe low surface brightness features and isolate nonthermal-emission regions at high energy. *Chandra's* superb angular resolution and modest spectroscopy allow us to isolate nonthermal emission regions that are intermixed with predominantly thermal emission (e.g., Hughes et al. 2000a). *Chandra* has already yielded two results that offer a glimpse of how it will improve our understanding X-rays from shock-accelerated electrons.

In Cas A, *Chandra* observations have shown that there is no clean separation between thermal and nonthermal components (Figure 2), as suggested by lower-angular-resolution studies (Holt et al. 1994). On the other hand, *Chandra* has revealed for the first time the precise locations of the forward and reverse shocks in Cas A (Gotthelf et al. 2000). The X-ray spectrum of the forward-shocked gas is very different from that of the dominant, reverse-shocked material. It requires the presence of a hard, featureless component absent from the reverse shock. Thus cosmic-ray acceleration appears to take place only near the forward shock. While this in itself is unsurprising, it points out that care must be taken in radio/X-ray comparisons, such as that carried out by Keohane & Reynolds (2000), to consider the radio emission only from those regions in which cosmic rays are accelerated.

The SNR 0540-693 in the Large Magellanic Cloud is a composite remnant whose plerion and pulsar have many properties in common with the Crab Nebula. The shell is dominated by thermal X-rays. A hard image (E higher than $\sim$2 keV) reveals two arcs of hard emission diametrically opposite one another along the rim (Figure 3). Whether these arise as a result of interaction between jets from the pulsar and the shock-compressed shell material, as in the old Galactic SNR W50 (Safi-Harb & Petre 1999), or from shock

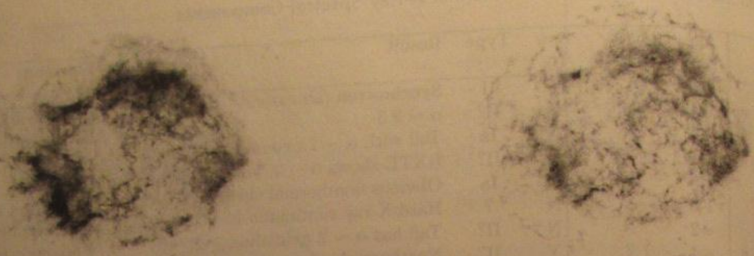

Fig. 2. (Left) Broad band *Chandra* image of Cas A. (Right) *Chandra* image of Cas A at energies above 3 ke The outer shock front is far more prominent than in the broad band image. A substantial fraction of the X-r flux front from this outer shock is contributed by a hard, featureless component. This component contribu much less, and could be absent, in the bright X-ray ring.

acceleration, as suggested by the morphological similarity to SN1006, has not been established.

DISCUSSION

The considerable and ever-increasing number of detections of hard, nonthermal emission associated wi the shocks of supernova remnants has allowed us to establish the following:

- The existence of nonthermal X-ray emission from the shocks of many supernova remnants. In at le some of these remnants the emission is synchrotron emission from electrons with energy around 1 TeV. This result is substantiated by the detection of TeV gamma rays from SN 1006 and G347.5-
- *Chandra* has already shown that the situation in these remnants is more complicated than previou thought. In particular, there is not necessarily a unique correspondance between the radio surfa brightness and the nonthermal X-ray emission. We need to revise our notion about how connect th radio and the X-ray fluxes in these remnants as much of the radio-emission regions apparently do n participate in cosmic-ray acceleration.
- There may be more than one mechanism for accelerating particles. In the middle aged remn IC 443, for instance, hard emission is localized to regions along the eastern rim where the SN shock is most strongly interacting with a molecular cloud (Keohane et al. 1997). Hydrodynami modeling indicates that enhanced particle acceleration can occur downstream from shock interacti with isolated cloudlets (Jones & Kang 1993), and this has been proposed as the mechanism to expl the hard emission in IC 443. The hard nonthermal X-ray emission in the lobes of the old remn W50 are thought to be produced by particle acceleration at the terminal shocks of the jets emana from SS 433 (Safi-Harb & Petre 1999).
- There seems to exist an emerging class of low-radio-flux, shell-like remnants, whose X-ray emis is dominated by synchrotron radiation. SN 1006 is the class prototype. Their properties ca ascribed to expansion in a low density medium. Finding new members of this class is an observati

Fig. 3. (Left) Broad band *Chandra* image of the Large Magellanic Cloud SNR 0540-693. (Right) *Chandra* image of 0540-693 at energies above 2 keV. The outer shock front is far more prominent than in the broad band image. A substantial fraction of the X-ray flux front from this outer shock is contributed by a hard, featureless component. This component contributes much less, and could be absent, in the bright X-ray ring.

challenge as these remnants' low radio surface brightness causes them to be overlooked or not detected in surveys.

In our discussions thus far we have only considered TeV electrons. Unfortunately, these observations to not allow us to test the relationship between these electrons and the protons and nuclei comprising the majority of cosmic rays. To understand that, we are forced rely on the inferences from shock-acceleration models (e.g., Ellision, Berezhko, & Baring 2000).

More importantly, these results do not resolve whether SNR's are responsible for accelerating most cosmic rays below the knee. The maximum energy of the electrons responsible for the X-ray emission is probably less than a few hundred TeV; the steepness of the X-ray synchrotron spectrum requires a turnover of the photon spectrum between the radio and X-ray bands, and thus the electron spectrum around a few tens of TeV. Depending on the mechanism responsible for the turnover, there could be serious implications for the more massive, positively-charged particles (e.g., Reynolds & Keohane 2000). If the turnover is due to the finite age of the remnant, then we will find no protons with higher energy. On the other hand, if the electron energy is governed by synchrotron losses or electron escape, then higher energy protons might be present.

One thing that seems likely is that shocks impart sufficient energy into particle acceleration to produce cosmic rays. Nonlinear-acceleration models suggest that 10 percent or more of the energy from the forward shock can be deposited in particles. Such models can successfully account for the emission from remnants like SN 1006 (Ellision, Berezhko, & Baring 2000). A recent *Chandra* result has provided the first observational support for these models. In the remnant E0102.2-7219 in the Small Magellanic Cloud, the very low ratio of the electron temperature to the shock velocity requires a second channel for substantial energy loss. The most likely such mechanism is particle acceleration (Hughes et al. 2000b). Curiously, the X-ray spectrum of this remnant shows no evidence for electron synchrotron radiation.

CONCLUSION

In a mere five years, we have made enormous progress using X-ray observations toward detrmining whether diffusive shock acceleration in supernova remnants is the primary mechanism for producing Galactic cosmic rays. While much work remains to be done before a definitive answer is obtained, with *Chandra* and *XMM/Newton* we have available the powerful observatories necessary for performing this task.

REFERENCES

Allen, G.E., Keohane, J. W., Gotthelf, E. V., Petre, R., Jahoda, K., et al., Evidence of X-Ray Synchro Emission from Electrons Accelerated to 40 TeV in the Supernova Remnant Cassiopeia A, *ApJ*, 487, L1 1997.

Allen, G.E., Gotthelf, E.V., & Petre, R., Evidence of 10-100 TeV Electrons in Supernova Remnants, P *26th International Cosmic Ray Conference*, **3**, 480, 1999.

Aschenbach, B., Discovery of a Young Nearby Supernova Remnant, *Nature*, **396**, 141, 1998.

Asvarov, A.I., Dogiel, V.A., Gusienov, O.H., & Kasumov, F.K., The Hard X-ray Emission of the You Supernova Remnants, *A&A*, **229**, 196, 1990.

Borkowski, K.J., Rho, J., Reynolds, S.P., & Dyer, K.K., Thermal and Nonthermal X-Ray Emission in S RCW 86, *ApJ*, in press, 2000.

Decourchelle, A., Ellison, D.C., & Ballet, J., Thermal X-Ray Emission and Cosmic-Ray Production in You Supernova Remnants, ,*ApJ*, **543**, L57, 2000.

Ellison, D.C., Berezhko, E.G., & Baring, M.G, Nonlinear Shock Acceleration and Photon Emission Supernova Remnants, *ApJ*, **540**, 292, 2000.

Gotthelf, E.V., Koralesky, B., Jones, T.W., Rudnick, L., Hwang, U., Petre, R., & Holt S.S., Detection the Forward and Reverse Shocks in Cassiopeia A, *ApJ*, submitted, 2000.

Hamilton, A.J.S., Sarazin, C.L. & Szymkowiak, A.E., The X-ray Spectrum of SN 1006, *ApJ*, **300**, 698, 19

Holt, S.S., Gotthelf, E.V., Tsunemi, H., & Negoro, H., ASCA Observations of Cassiopeia A, *PASJ*, 4 L151, 1994.

Hughes, J.P., Rakowski, C.E., Burrows, D.N., & Slane, P.O., Nucleosynthesis and Mixing in Cassiopeia *ApJ*, **528**, L109, 2000a.

Hughes, J.P., Rakowski, C.E., & Decourchelle, A., Electron Heating and Cosmic Rays at a Supernova Sh from *Chandra* X-ray Observations of E0102.2-7219, *ApJ*, 543, L61, 2000b.

Jones, T.W., & Kang, H., Cosmic-Ray Acceleration During the Impact of Shocks on Dense Clouds, *A* **402**, 560, 1993.

Keohane, J.W., Petre, R., Gotthelf, E.V., Ozaki, M., & Koyama, K., A Possible Site of Cosmic R Acceleration in the Supernova Remnant IC 443, *ApJ*, **484**, 350, 1997.

Keohane, J.W., High Energy Particle Acceleration and Turbulent Magnetic Field Amplification in Sh Type Supernova Remnants, Ph.D. Thesis, University of Minnesota, 1998.

Koyama, K., Petre, R., Gotthelf, E.V., Hwang, U., Matsuura, M., Ozaki, M., & Holt, S.S., Evidence f Shock Acceleration of High-Energy Electrons in the Supernova Remnant SN 1006, *Nature*, **378**, 255, 19

Koyama, K., et al., Discovery of Non-Thermal X-Rays from the Northwest Shell of the New SNR RX J1713 3946: The Second SN1006?, *PASJ*, **49**, L7, 1997.

Laming, J.M., A Thermal Model for the Featureless X-Ray Emission from SN 1006?, *ApJ*, **499**, L309, 19

Muraishi, H., Tanimori, T., Yanagita, S., Yoshida, T., Moriya, M., et al., Evidence for TeV Gamma-R Emission from the Shell Type SNR RX J1713.7-3946, *A&A*, **354**, 57, 2000.

Reynolds, S.P., Synchrotron Models for X-Rays from the Supernova Remnant SN 1006, *ApJ*, 459, L1 1996.

Reynolds, S.P., & Keohane, J.W., Maximum Energies of Shock-Accelerated Electrons in Young Shell S pernova Remnants, *ApJ*, **525**, 368, 1999.

Tanimori, T., Hayami, Y., Kamei, S., Dazeley, S. A., Edwards, P. G., et al., Discovery of TeV Gamma Ra from SN 1006: Further Evidence for the Supernova Remnant Origin of Cosmic Rays, *ApJ*, 497, L 1998.

Tatischeff, V., Ramaty, R., & Kozlovsky, B., X-Rays from Accelerated Ion Interactions, *ApJ*, 504, 8 1998.

Safi-Harb, S., & Petre, R., Rossi X-Ray Timing Explorer Observations of the Eastern Lobe of W50 Associ with SS 433, *ApJ*, **512**, 784, 1999.

Slane, P., Hughes, J.P., Edgar, R.J., & Plucinsky, P.P., G266.2-1.2: Another Nonthermal Shell-Type SN *BAAS*, **195**, 3306, 1999.

Tomida, H., Synchrotron Emission from the Shell-Like Supernova Remnants and the Cosmic Ray Ori Ph.D. Thesis, Kyoto University, 2000.

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