On the Nature of the Nonthermal Emission from the Supernova Remnant IC 443

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Abstract. The supernova remnant (SNR) IC 443 is a nearby (~ 1.5 kpc) remnant of intermediate age which appears to be interacting with a molecular cloud and is spatially coincident with the unidentified EGRET source 3EG J0617+2238. We present new spectra of IC 443 obtained using the PCA on *RXTE*. The spectrum is well fit by a two-component model consisting of a non-equilibrium ionization collisional plasma model with kT~0.6 keV plus a power-law with index ~2.2. We compare our results with the earlier results of *HEAO 1* A-2, *Ginga*, *ASCA*, and *BeppoSAX*, and find generally good agreement. We also discuss the possible association of 3EG J0617+2238 with IC 443 given that recent *Chandra* results indicate that much of its nonthermal X-ray emission originates from a pulsar wind nebula. We find that unless the calculation of the position of 3EG J0617+2238 is affected by nearby strong sources such as Geminga, the *Chandra* source is excluded from being associated with the EGRET source.

INTRODUCTION

IC 443 is a canonical mixed-morphology SNR that has a complex morphological structure due to interactions with local molecular clouds. In particular, Braun & Strom [1] have characterized the morphology of IC 443 as a series of three interconnected shells resulting from these interactions. The distance to IC 443 is somewhat uncertain but is generally thought to be 1.5-2.0 kpc [1,2,3,4].

The age of IC 443 has been controversial until very recently. Using X-ray observations made with the *Einstein Observatory* and the *HEAO 1* A-2 experiment, Petre et al. [5] determined the age of IC 443 to be between 2800 and 3400 years. More recently, Chevalier [6] has modeled IC 443 as an explosion inside a molecular cloud and suggests an age of about 30,000 years, which was confirmed by Olbert et al. [7].

IC 443 is particularly interesting because it has been observed to emit a non-thermal X-ray spectrum up to ~15 keV [8,9,10] and thus it belongs to the select subclass of SNRs that exhibit non-thermal X-ray emission which includes Cas A [11], SN 1006 [12], and G347.3-0.5 [13]. It is also spatially-coincident with an unidentified high-energy gamma-ray source seen by the EGRET experiment on the *CGRO* [14,15,16].

RXTE PCA OBSERVATION OF IC 443

IC 443 was observed using the Proportional Counter Array (PCA) on *RXTE* between August 13 and 16, 1996 with the 1^o field-of-view (FOV) centered at $\alpha = 6^h\ 17^m\ 1.5^s$, $\delta = +22^o\ 34'\ 52.3''$ (J2000) and a net exposure time of 35,488 seconds. Analysis of the data was performed using the standard suite of FTOOLS and the latest background model developed for faint sources , L7-240. A detailed description of the analysis method can be found on the HEASARC website.

The spectrum we derived is for the spatially integrated X-ray emission from the SNR. We fit the combined data from all observation segments in XSPEC using a two-component model that included a thermal and non-thermal power-law component. We found that the generalized nonequilibrium ionization model (gnei) [17] best characterized the low-energy thermal component of the spectrum. We show the results of the fitting procedure in Figure 1 and list the best-fit parameters in Table 1. We find that the high-energy X-ray spectrum of IC 443 can be well characterized by a power-law to energies beyond 20 keV. A two-temperature thermal (gnei) model can also adequately fit the data ($\chi_\nu^2 = 1.66$) with temperatures of 0.63 keV and 12.4 keV but this requires an unacceptably large absorbing column of $5.2\text{x}10^{22}$ cm^{-2} which we feel invalidates this model.

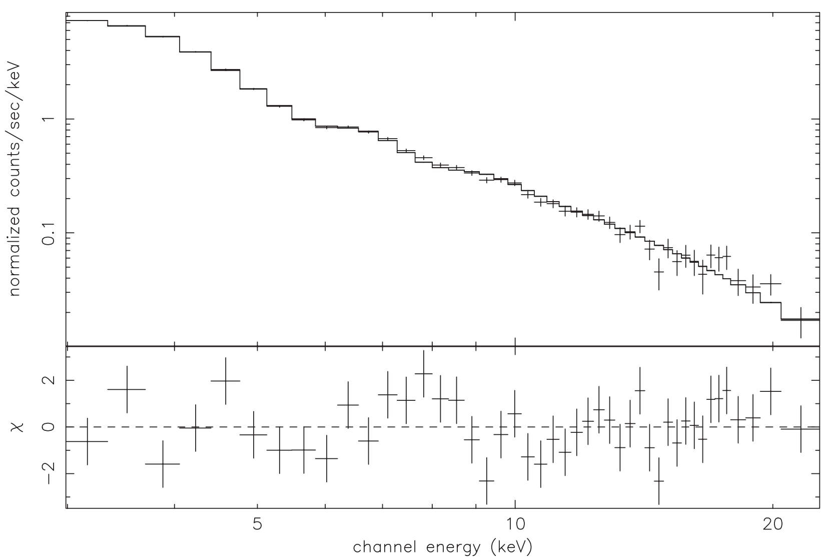

FIGURE 1. *RXTE* PCA data for IC 443 with the best-fit folded gnei+pow model. Also plotted are the residuals in units of χ^2.

TABLE 1. Best-Fit Model Parameters.

Parameter	Best-Fit Value	1σ Error
n_H (x10^{22} cm^{-2})	0.89	+0.44/-0.41
kT (keV)	0.60	+0.009/-0.018
τ (kyr cm^{-3})	18.97	+1.07/-7.46
<kT> (keV)	1.89	+0.26/-0.10
Photon Spectral Index	2.21	+0.07/-0.07
χ_ν^2	1.32	

In Table 2 we compare the *RXTE* PCA spectral results with those of previous missions. Since this is a heterogeneous set of observations, it is difficult to precisely compare the results. We find that our *RXTE* PCA results closely match those from the *Ginga* LAC, except that Wang et al. [10] report a significantly higher integrated flux in the 2-20 keV band. Keohane et al. [9] previously suggested the possibility of a calibration discrepancy between the *Ginga* LAC and *ASCA* GIS because of similar discrepancies in the observed fluxes.

Keohane et al. [9] found that ~60% of the remnant-integrated 7 keV emission could be attributed to 2 unresolved sources in the south-central region (Source A) and eastern rim (Source B) of IC 443. Source A was found to contribute ~40% of the total 7 keV emission and its spectrum can be well characterized by a thermal+nonthermal two-component model with kT = 0.89 keV and spectral index = 2.3. Our integrated 2-10 keV flux is consistent with that observed by Keohane et al. [9]. The spectral index we derive for the nonthermal component is consistent with the index they derived for Source A as would be expected if Source A is indeed the largest source of >7 keV photons in the field-of-view.

We find that our spectral index is marginally consistent with the index of Source A determined by Bocchino & Bykov [8] using the *BeppoSAX* MECS. Their best-fit spectrum, a single power law with index 1.96, is significantly harder than any of the previously derived spectra for either IC 443 in its entirety or for Source A in particular. The 2-10 keV integrated flux from Source A + Source B is also significantly higher than both that observed by *RXTE* PCA for the entire remnant as well as that reported by Keohane et al. [9] using the *ASCA* GIS. On the other hand it appears consistent with the flux reported by Wang et al. [10].

TABLE 2. Comparison of *RXTE* PCA Fit Parameters with Other Mission Results.

Instrument	Source	n_H (10^{22} cm^{-2})	kT (keV)	Spectral Index	Integrated Flux (10^{-11} ergs/cm^2/s)
HEAO 1 A-2 MED	Entire SNR	-----	1.05 (+0.29,-0.25)	-----	7±1 (2-10 keV)
Ginga LAC	Entire SNR	0.79	0.68	2.2	9 (2-20 keV)
ASCA GIS	Source A	0.18±0.03	0.89*	2.3±0.2	-----
	Source B	<0.03	0.89*	0.1±1.3	-----
	~SNR†				5±1 (2-10 keV)
BeppoSAX MECS	Source A	-----	-----	1.96 (+0.21,-0.12)	7.5±1.2 (2-10 keV)
	Source B	-----	1.07 (+0.23,-0.31)	1.5±0.9	1.8±0.2 (2-10 keV)
RXTE PCA	Entire SNR	0.89 (+0.44,-0.41)	0.60 (+0.009,-0.018)	2.21±0.07	6.22 (2-10 keV) 6.62 (2-20 keV)

*Fixed at off source value

†Summed over 2 GIS fields-of-view, estimated to be ~90% of total SNR emission

IS 3EG J0617+2238 ASSOCIATED WITH IC 443?

The EGRET experiment on the *Compton Gamma Ray Observatory* has found a 17.4σ source, 3EG J0617+2238, that is spatially consistent with IC 443 [14,15,16]. The spectrum of this source is well fit by a power-law with index 1.98, a broken power-law with index 1.79 below 1 GeV and 2.65 above 1 GeV, and a 1.68 power-law with exponential cut-off at 2.2 GeV [18]. The source shows very marginal variability [19], so that there is no evidence that it is a background blazar.

This lack of variability and its positional coincidence with IC 443 have led to proposals that this EGRET source is due either to locally accelerated cosmic rays [20,21,22,23] or a radio-quiet pulsar [24]. Both models have their merits. SNRs have long been thought to be the sources of the Galactic cosmic rays [25] and there is very strong evidence that IC 443 is interacting with dense interstellar clouds [26,27]. The discovery that Geminga was a radio-quiet, gamma-ray emitting pulsar [28] has also led to speculation about the Galactic population of such objects and their contribution to the population of unidentified EGRET sources. Here we examine these possibilities in light of the recent X-ray observations of the region.

Recently, Olbert et al. [7] have shown, using the *VLA* and *Chandra*, that Source A is a comet-shaped nebula of hard emission which contains a softer point source at its apex. They have designated this source CXOU J061705.3+222127, and have argued that this structure is a pulsar and an associated wind nebula. Not much is known about Source B. As shown in Table 2, its spectrum is harder than Source A/CXOU J061705.3+222127.

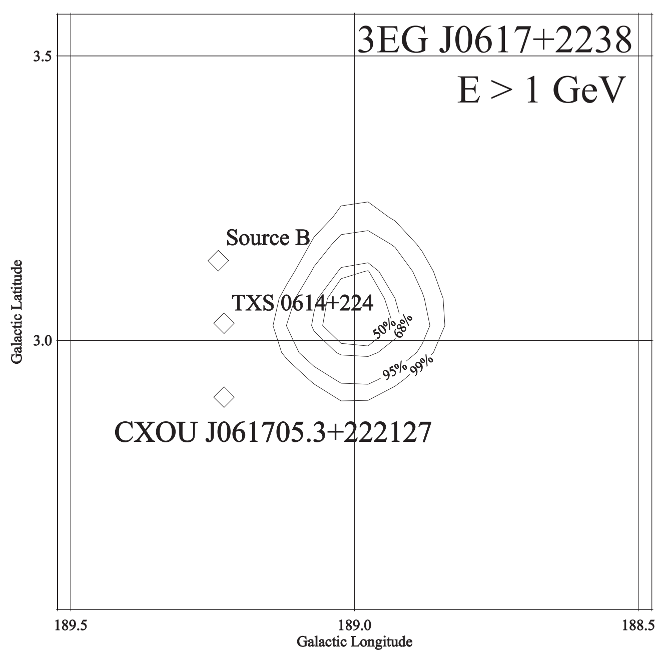

FIGURE 2. This plot shows the 50%, 68%, 95%, and 99% confidence contours for the EGRET source 3EG J0617+2238 for photons >1 GeV [14]. Also shown are the positions of the two hard X-ray sources seen by *ASCA*, *BeppoSAX*, and *Chandra*, as well as the radio source TXS 0614+224 which is thought to be extragalactic. Note that all of the sources are positionally inconsistent at the 99% confidence level.

In addition to these sources, there is a radio source in the same region which is thought to be extragalactic in origin [29]. This radio source was seen at flux densities of 2.1 Jy at 151 MHz and < 0.2 Jy at 1419 MHz. We identify the radio source with the source TXS 0614+224 [30].

We plot the EGRET location for 3EG J0617+2238 for photons energies >1 GeV as well as the locations of the X-ray and radio sources in Figure 2. Note that all of these sources are outside the 99% confidence contour and are offset from the most likely gamma-ray source position by ~15'. Even though the spectrum of the EGRET source is pulsar-like [31], this offset suggests that the EGRET source and the pulsar nebula are unrelated unless the EGRET source position has been affected by the presence of strong nearby sources beyond the currently understood systematics [32]. Deep observations of the region containing the GeV source with new, powerful x-ray instruments such as *Chandra* and *XMM* are necessary to probe for possible x-ray counterparts to the high-energy gamma-ray source.

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