1. INTRODUCTION

The possibility of supernova remnants (SNRs) being sources of observable GeV emission has long been suggested by theoretical models of cosmic-ray acceleration (see Baring et al. 1999 and references therein) in SNR shocks and by statistical associations with cataloged γ-ray sources (Sturmer & Dermer 1995; Esposito et al. 1996; Yadigaroglu & Romani 1997). However, the direct linking of a particular SNR with a specific γ-ray source detected by the EGRET instrument on board the Compton Gamma-Ray Observatory has been elusive (Doherty et al. 2003; Torres et al. 2003; note that we only refer to the results of the supernova blast as SNR, not isolated pulsar wind nebulae [PWNe] which are sometimes referred to as “plerionic” or “Crab-like” SNR). The EGRET sources with the smallest and most robust error boxes are sometimes referred to as “plerionic” or “Crab-like” SNR. The EGRET sources with the smallest and most robust error boxes are not positionally coincident with regions of SNRs that show direct evidence of high-energy particle acceleration through synchrotron emission of X-rays. Although there are five previously known radio SNRs that contain within their shells unidentified EGRET sources that are bright above 1 GeV (as defined by Lamb & Maccormak 1997), in no case can hard X-ray emission from the SNR blast wave be convincingly associated with the γ-ray source (Roberts et al. 2001a, hereafter RRK01).

Interestingly, four of these SNRs are of the subclass of mixed-morphology SNR (Rho & Petre 1998), which have centrally concentrated thermal X-ray emission within a radio shell. Three of these (CTA 1, IC 443, and W44) also contain young, energetic pulsars that are actively producing high-energy particles, as evidenced by their wind nebulae [PWNe] which are sometimes referred to as “plerionic” or “Crab-like” SNR. The EGRET sources with the smallest and most robust error boxes are not positionally coincident with regions of SNRs that show direct evidence of high-energy particle acceleration through synchrotron emission of X-rays. Although there are five previously known radio SNRs that contain within their shells unidentified EGRET sources that are bright above 1 GeV (as defined by Lamb & Maccormak 1997), in no case can hard X-ray emission from the SNR blast wave be convincingly associated with the γ-ray source (Roberts et al. 2001a, hereafter RRK01).

We report the discovery of a partial ~2° diameter nonthermal radio shell coincident with Taz, the pulsar wind nebula (PWN) in the error box of the apparently variable γ-ray source 3EG J1809–2328. We propose that this radio shell is a newly identified supernova remnant (SNR G7.5–1.7) associated with the PWN. The SNR surrounds an amorphous region of thermal X-rays detected in archival ROSAT and ASCA observations, putting this system in the mixed-morphology class of supernova remnants. G7.5–1.7 is the fifth such supernova remnant coincident with a bright GeV source, and the fourth containing a pulsar wind nebulae.

Subject headings: gamma rays: observations — ISM: individual (G7.5–1.7) — pulsars: individual (Taz) — radio continuum: ISM — supernova remnants — X-rays: ISM

2. ANALYSIS OF ARCHIVAL X-RAY DATA IN THE REGION SURROUNDING THE TAZ PWN

3EG J1809–2328 is one of the brightest sources of >1 GeV emission in the Galaxy (Hartman et al. 1999; Lamb & Maccormak 1997). It has a well-determined position (Fig. 1) and apparently variable emission above 100 MeVon timescales of months (Nolan et al. 2003). ASCA imaging of the EGRET error box revealed an extended hard X-ray source (RRK01), which (Braje et al. 2002) subsequently resolved into an apparently rapidly moving PWN (RPWN) and a young stellar cluster using a short Chandra observation (see Kaspi et al. 2006; Gaensler & Slane 2006 for general reviews of PWN). Radio imaging with the VLA and observations with XMM-Newton confirm the RPWN nature of the X-ray source (Roberts et al. 2001b; Braje et al. 2002; M. S. E. Roberts et al. in preparation). Due to the radio nebula’s distinctive funnel shape (presumably imposed by its motion), its unusually powerful γ-ray emission, and the growing tradition of naming PWNe after animals,
this nebula is sometimes referred to as “Taz” (short for Tasmanian devil).

The X-ray and radio morphology of Taz, if interpreted as being created by a bow shock, suggests a birth site to the northwest. A ROSAT PSPC exposure-corrected 0.1–2.4 keV image obtained through SkyView shows a large region of soft X-ray emission in this direction, which we will refer to as G7.5–1.7 (Fig. 1). This inspired a 38 ks observation with the ASCA satellite on 1996 September 24 that has not previously been published. Following the imaging and spectral fitting procedures outlined in RRK01, we produced combined particle background-subtracted, exposure-corrected images of the 3EG J1809–2328 and G7.5–1.7 fields from the ASCA GIS data in the 0.7–2 keV, 2–10 keV, and 4–10 keV bands (Fig. 2). The higher energy bands show a fairly bright, compact source of hard X-rays in the region of soft thermal X-ray emission which is not evident in the ROSAT image. The peak of this source is at R.A. = 18°08′56.3″, decl. = −23°09′57″ (J2000) in the GIS 2–10 keV image; ASCA images have a nominal positional error of ~24″ (Gotthelf et al. 2000). We will refer to this hard source as AX J1808.9–2310.

We extracted spectra from two regions in the field of the GIS instruments, one containing the hard source and one containing the soft diffuse emission. Since there is emission essentially throughout the ASCA field, we used a background region from the neighboring field which contains the Taz PWN. We fit the soft extended emission to a thermal model, choosing an absorbed vnei nonequilibrium model from XSPEC to facilitate comparison with other mixed-morphology remnants, at first keeping the abundances fixed to solar. To help constrain the soft end of the thermal emission spectrum, we simultaneously fit the ROSAT PSPC spectrum extracted from the same region. We obtained an adequate fit using a single temperature with solar abundances. The result is a temperature $kT = 0.61^{+0.08}_{-0.05} \text{keV}$ (90% confidence region), an ionization timescale $\tau = 1.54^{+0.80}_{-0.47} \times 10^{11} \text{s cm}^{-3}$, and an absorption $n_H = 1.5^{+0.6}_{-0.5} \times 10^{21} \text{cm}^{-2}$. Note that the ROSAT and ASCA spectra seemed to differ somewhat near the upper end of the ROSAT passband (~2 keV), and so these values are somewhat dependent on which energy bins from ROSAT were included in the fits. For example, ignoring the ROSAT data above 1.6 keV resulted in an improved $\chi^2$ and a somewhat lower absorption of $\sim 9 \times 10^{20} \text{cm}^{-2}$. Fitting the ASCA data by themselves resulted in consistent values, and allowing the abundances to vary did not result in a significantly better fit. We also tried the $\nu$ ray and $\nu$ ray equilibrium thermal models, but these resulted in statistically inferior fits. The spectral values obtained are typical of temperatures and timescales fit from ASCA observations of other mixed-morphology SNRs (Kawasaki et al. 2005). Since the thermal X-ray emission covers an area much larger than the field of view of the ASCA GIS, and since the total extent even in the ROSAT images is somewhat unclear, an accurate total thermal flux measurement is difficult. However, using the fluxed ROSAT maps and extrapolating from our fit spectra, we estimate the total unabsorbed bolometric thermal flux from the remnant to be on the order of $10^{-10} \text{erg cm}^{-2} \text{s}^{-1}$.

We then fit the hard source (AX J1808.9–2310) to an absorbed power law plus an absorbed vnei model, fixing the latter to the values above, allowing only the normalization to vary. The result is an absorption $n_H = 1.9^{+0.5}_{-0.4} \times 10^{22} \text{cm}^{-2}$, a spectral index $\Gamma = 2.57^{+0.29}_{-0.27}$, and a 2–10 keV flux $F_X = 3.9 \pm 0.1 \times 10^{-17} \text{ergs cm}^{-2} \text{s}^{-1}$. Since there is no evidence for a source of additional foreground absorption in the mid-infrared or optical (see below), the order of magnitude higher absorption toward this source suggests it is an unrelated background object and/or contains significant intrinsic absorption. The total Galactic $n_H$ in

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1 The NASA SkyView Observatory is located at [http://skyview.gsfc.nasa.gov/](http://skyview.gsfc.nasa.gov/).
this direction as estimated using the HEASARCln tool and the H \textsc{i} maps of Dickey & Lockman (1990) is \( \sim 6 \times 10^{21} \) cm\(^{-2}\).

3. RADIO OBSERVATIONS

We observed the region around Taz at 90 cm with the VLA on 2004 May 28 in the DnC configuration (project code AR 547) for 4.5 hr (on-source). We used 32 channels over a bandwidth of 12.6 MHz in LL and RR polarizations. Using AIPS and standard SNRs are labeled for reference (Griffith et al. 1994; Lockman et al. 1996; Brogan et al. 1990). 90 cm images were masked at 30 and 120 mJy beam\(^{-1}\), respectively. Contours from the 168\(\times\)120\(\prime\) resolution 90 cm image are superposed; the contour levels are 60 \(\times\) (1, 2, 3, 4, 5) mJy beam\(^{-1}\). Several previously identified H \textsc{i} regions and SNRs are labeled for reference (Griffith et al. 1994; Lockman et al. 1996; Brogan et al. 2006).

**Fig. 3.**—Spectral index (assuming \( S_0 \)) map of G7.5–1.7 and the surrounding region derived from an 11 cm Bonn image and the 90 cm VLA image. Before calculating the spectral index, the Bonn image was passed through a “high-pass” filter to mimic the spatial coverage of the VLA interferometric data (which are not sensitive to smooth structures larger than 1\(\prime\)). The 90 cm image was first convolved to the 258\(\prime\) resolution of the Bonn image. The input 11 and 90 cm images were masked at 30 and 120 mJy beam\(^{-1}\), respectively. Contours from the 168\(\times\)120\(\prime\) resolution 90 cm image are superposed; the contour levels are 60 \(\times\) (1, 2, 3, 4, 5) mJy beam\(^{-1}\). Several previously identified H \textsc{i} regions and SNRs are labeled for reference (Griffith et al. 1994; Lockman et al. 1996; Brogan et al. 2006).

4. DISCUSSION

G7.5–1.7 has the classic properties of a mixed-morphology supernova remnant (Rho & Petre 1998). The thermal X-ray emission is concentrated between Taz and the Galactic plane side of the radio shell. In both the Bonn 11 cm and our VLA 90 cm images, between 1/2 and 3/4 of a radio shell surrounds Taz. The side toward the Galactic plane is brightest, while the side away from the plane is too faint to be sure of any structures, suggesting a strong density gradient in this direction. Comparing to the MSX 8.3 \(\mu\)m image, the radio shell is located within a region of low, diffuse mid-infrared emission. Numerical models of the evolution of mixed-morphology remnants suggest they are a common stage in the growth of remnants at ages of \(\sim\)10,000–100,000 yr if they are expanding in high-density regions of the ISM (Tilley et al. 2006). In this case, where there is an apparent density gradient, the thermal X-ray emission is concentrated near the bright side of the shell, toward the Galactic plane, rather than around the apparent center of the shell.

The position of the center of G7.5–1.7 suggests that it is the birth remnant of Taz. While the overall X-ray absorption of Taz is significantly higher \((n_{\text{H}} \sim 1.8 \times 10^{22} \text{ cm}^{-2}; \text{RRK01}), it is also moving into or behind the Lynds 227 dark cloud. XMM-Newton imaging shows that some parts of the X-ray nebula are absorbed more than others (Roberts et al. 2006), and a preliminary spectral analysis suggests a range of \(n_{\text{H}} \sim 0.7–2.0 \times 10^{22} \text{ cm}^{-2}\). If we assume Taz and G7.5–1.7 are associated, then the distance to Lynds 227 of 1.7 kpc (Oka et al. 1999) can be considered a lower limit to G7.5–1.7.

From the above estimates of the center of the radio shell, and the pulsar wind nebula line of symmetry, we estimate the birth site of Taz to be \(l \sim 7.53\(^\circ\), \(b \sim -1.68\(^\circ\). The average transverse space velocity is then implied to be \(v_T \sim 200(d_{1.7}/500) \text{ km s}^{-1}\), fairly typical for an isolated pulsar. Here \(d_{1.7}\) is the distance in units of 1.7 kpc and 500 is the age in units of 50 kyr. The distance from this estimated birth site to the pulsar is about half the average distance to the shell \((R_b \sim 0.62\(^\circ\)), which is roughly where a bow shock is expected to begin forming around a pulsar moving within a decelerating SNR shell (van der Swaluw et al. 2004).

If we accept the association with the pulsar and hence the distance to Lynds 227 as a lower limit on the SNR distance, and we further assume it has been undergoing Sedov expansion for \(\alpha \sim -0.3\) to \(-0.7\), with an estimated uncertainty of \(\pm 0.3\) at any particular position. The large uncertainty is dominated by the inherent uncertainty in measuring flux from a large, diffuse object with an interferometer, and not the noise in the images.

The center of the radio shell is at roughly \(l \sim 7.54\(^\circ\), \(b \sim -1.90\(^\circ\) near the northern edge of the Taz radio nebula, and the radius is \(r \sim 0.82\(^\circ\). The shell has a somewhat smaller radius of curvature \((r \sim 0.45\(^\circ\) center at \(l \sim 7.51\(^\circ\), \(b \sim -1.42\(^\circ\)) on the side nearer the Galactic plane, centered in the middle of the thermal X-ray emission. Assuming that the origin of the expanding shell lies somewhere in between these two centers and near the symmetry axis of Taz, we will refer to the radio shell as G7.5–1.7.

We have also obtained high-resolution \((3.6\(^\prime\) \times 3.2\(^\prime\)) 20 cm VLA data of a much smaller field of view centered on the Taz nebula, which will be discussed in detail in a future paper that concentrates on the PWN (M. S. E. Roberts et al., in preparation). For the purpose of the present paper it is interesting to note that there is a 13 mJy 20 cm radio source at R.A. = 18:08:57.59\(^\prime\), decl. = \(-23:09:45.4\) (J2000.0) that is coincident with the hard ASCA source AX J1808.9–2310. The radio source is elongated and well fit by a \(4.7\(^\prime\) \times 1.4\(^\prime\) Gaussian, suggestive of a barely resolved double-jet source.
the majority of its existence (i.e., $R \approx 10^4$), then we can estimate the current expansion velocity of the shell to be $v_t \approx 150(d_{15}/l_{50}) \text{ km s}^{-1}$. Note that if the SNR were considerably younger (e.g., $t \approx 15,000$ yr), or considerably farther away ($d \approx 5$ kpc), then the velocity of the radio shell would be similar to very young SNRs. For example, only a few degrees away on the sky is the X-ray and radio bright shell of the very young SNRs. For example, only a few degrees away on the sky is the X-ray and radio bright shell of the very young SNRs. For example, only a few degrees away on the sky is the X-rays emission and overall low absorption. However, at the estimated velocity of $\sim 150$ km s$^{-1}$, given our nominal distance and age, the bulk of the shock emission would be emitted well below 1 keV where absorption is more important and ROSAT is much less sensitive. Therefore, the lack of bright X-ray emission associated with the radio shell is consistent with the interpretation of $G7.5 - 1.7$ being at a distance of $\sim$2 kpc and an age similar to other mixed-morphology SNRs.

$G7.5 - 1.7$ is now the fifth known mixed-morphology supernova remnant that is coincident with the error box of one of the 25 brightest sources of GeV emission in our Galaxy, and the fourth of these to contain a pulsar wind nebula. Two of these SNRs also contain known TeV sources, and several other PWNe associated with bright GeV sources have TeV emission (Funk et al. 2008), so it is quite plausible that $Taz/G7.5 - 1.7$ also has TeV emission. However, in no currently known case is the GeV emission convincingly arising from the same spatial location as the TeV emission. This suggests that GeV and TeV emission may have separate sites of acceleration or represent particle populations with very different ages.

As is the case with the PWNe in CTA1 and W44, Taz is actually contained within the GeV error box, while the radio shells are outside the error box. In all three of these cases, there is some evidence of moderate variability of the $\gamma$-ray emission, with the source containing Taz showing the strongest evidence (Nolan et al. 2003). The W44/PSR B1853+01 system is very similar in that there is clearly an RPWN seen in both radio and X-rays at the edge of the thermal X-ray emitting region. It also has similar X-ray (Kawasaki et al. 2005) and $\gamma$-ray properties (RRK01). The rapid motion of the pulsars through the clumpy, dense interior of these remnants provides a natural variability mechanism for emission coming from the immediate environment of the pulsar. However, PSR B1853+01 is only moderately energetic, with a spin-down power $\dot{E} = 4.3 \times 10^{35}$ erg s$^{-1}$. Therefore, if this is where the variable $\gamma$-rays from W44 are produced, then it suggests that the interaction of a pulsar wind with the unique hot and dense environment of the interior of mixed-morphology remnants may allow for very efficient $\gamma$-ray production.

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Facilities: MSX, Effelsberg, ASCA (GIS), VLA, ROSAT (PSPC)

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