1. INTRODUCTION

Supernova remnants (SNRs) are considered the leading candidates for the accelerators of cosmic rays to at least the "knee" of the cosmic-ray energy spectrum ($E \approx 3000$ TeV). While the relationship between SNRs and cosmic-ray acceleration has received extensive attention in the literature (Bell 1978a, 1978b; Axford 1981; Blandford & Eichler 1987; Jones & Ellison 1991; Malkov & Drury 2001), most of this discussion has been theoretical, with only a limited amount of observational data to consider. One major unresolved issue related to cosmic-ray acceleration by SNRs is the maximum energy $E_{\text{cutoff}}$ attained by cosmic-ray particles accelerated by the shock front: for samples of young shell-type X-ray–emitting SNRs located in the Galaxy and the Large Magellanic Cloud, Reynolds & Keohane (1999) and Hendrick & Reynolds (2001) estimated values of $\leq 200$ TeV and $\leq 80$ TeV, respectively, for $E_{\text{cutoff}}$ for cosmic-ray electrons, both well below the knee of the cosmic-ray energy spectrum. Progress on this issue has been limited by the lack of both X-ray and TeV observations of SNRs with the angular and spectral resolution needed to probe the acceleration process.

Recently, however, high spatial resolution observations of SNRs at X-ray energies have become feasible using such X-ray observatories as ROSAT, ASCA, Chandra, and XMM. These high-resolution observations yield spatially resolved spectroscopy of X-ray–emitting features within the SNR, particularly the X-ray–luminous rims that are associated with the expanding shock fronts of SNRs. By performing a detailed spectral analysis of X-ray emission from the rims of SNRs, corresponding to shock fronts where interstellar or circumstellar material is being swept up, the cosmic-ray acceleration process can be probed. Initial insights on cosmic-ray acceleration by SNRs have been gleaned from ROSAT, ASCA, and RXTE observations of the high-energy X-ray emission from such SNRs as Cas A and SN 1006 (Willingale et al. 1996; Allen et al. 1997; Keohane...
1.2) are presented in § 4.1, our search for thermal X-ray emission from different regions of this SNR (§ 4.2), and the nature of the weak emission line found in the RXTE PCA spectrum of this source (§ 4.3). In our RXTE PCA data, we have searched for pulsed X-ray emission from the recently detected radio pulsar, which is possibly associated with the discrete X-ray source seen at the center of G347.3—0.5; we describe this search in § 4.4. A study of the broadband spectrum of the northwestern rim of G347.3—0.5 from radio to γ-ray wavelengths is presented in § 5. Comparisons between G347.3—0.5 and two similar SNRs (SN 1006 and G266.2—1.2) are presented in § 6, and conclusions are given in § 7.

2. OBSERVATIONS AND DATA REDUCTION

In this section we discuss the X-ray observations that were used in this analysis, including the instruments used and the data-reduction processes. These observations include archived data from observations of G347.3—0.5 that were made using the Position Sensitive Proportion Counter (PSPCB, hereafter just PSPC) of ROSAT and the Gas Imaging Spectrometer (GIS) of ASCA. We also include
our observations of this SNR using the Proportional Counting Array (PCA) of the *Rossi X-Ray Timing Explorer* (RXTE). These data sample the X-ray emission from G347.3−0.5 over nearly two full decades of energy (0.5–30 keV). Details of the observations for each instrument are provided in Table 1.

### 2.1. ROSAT PSPC Observations and Data Reduction

**ROSAT** observed G347.3−0.5 at a location near the center of the remnant using the PSPC, a multiple-wire proportional counter sensitive to photons that have energies between approximately 0.1 and 2.0 keV. The energy resolution \( \Delta E/E = 0.43 \) at 0.93 keV, and the field of view of the telescope is \( 2^\circ \). For our off-axis observations, the angular resolution is \( \approx 50'' \) (50% encircled-photon radius), and the maximum on-axis effective area of the system is about 260 cm\(^2\) (Pfeffermann et al. 1987).

Spectra were constructed using the PSPC data for four spatially separate regions: the luminous northwestern and southwestern rims, the northeastern rim, and the interior region. This final region was considered in order to analyze diffuse emission from the interior of the SNR. Emission from the two bright interior point sources, 1WGA J1714.4−3945 and 1WGA J1713.4−3949 (Pfeffermann & Aschenbach 1996; Slane et al. 1999), were subtracted from this region before a spectrum was extracted. The former source appears to be associated with a foreground star, while the latter may be the X-ray counterpart to a recently discovered radio pulsar. This radio pulsar may in turn be associated with G347.3−0.5; we discuss this source in more detail in §4.4. An image from the PSPC observation appears in Figure 1, with the positions of these regions indicated. Fits to the spectra extracted from these regions are described in §3.2.

### 2.2. ASCA GIS Observations and Data Reduction

The instruments on *ASCA* (Tanaka, Inoue, & Holt 1994) observed locations on the southwestern rim, the northwestern rim, and the northeastern rim of G347.3−0.5. While both the GIS and the Solid State Imaging Spectrometer (SIS) aboard *ASCA* collected data during these observations, the GIS has a larger field of view so only the data from the GIS were considered for the present study. The GIS consists of two units (GIS2 and GIS3) of imaging gas scintillation proportional counters with a sealed-off gas cell equipped with an imaging phototube; for our research, we only considered data collected by the GIS2 unit. The GIS is sensitive over the energy range of approximately 0.7–10 keV and has an energy resolution of \( \Delta E/E = 0.078 \) at 6 keV (Ohashi et al. 1996; Makishima et al. 1996). The field of view of the GIS is 22' in radius and the maximum effective area for our off-axis observations is 94 cm\(^2\) at 2.07 keV. The data from these observations were reduced using standard *ASCA* GIS reduction techniques as described in the *ASCA* Data Reduction Guide, Version 2.0. The reduction process filtered data for elevation angle, stable pointing directions, the South Atlantic Anomaly, and cutoff rigidity. The data were also screened for characteristics of the GIS internal background and screening based on event locations and rise time. The standard script ASCASCREEN was run in order to accomplish much of this reduction. We extracted spectra for the northwestern rim, the southwestern rim, and the northeast rim of the SNR using the same regions as in the *ROSAT* PSPC spectral analysis. Fits to these spectra are discussed in detail in §3.2.

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**Fig. 1.—** *ROSAT* PSPC image of G347.3−0.5 from Slane et al. (1999). Note the X-ray–luminous northwestern rim (a TeV source) as well as the bright southwestern and northeastern rims. Contour levels start at 1.44 counts arcmin\(^{-2}\) s\(^{-1}\) and increase upward in steps of 1.15 counts arcmin\(^{-2}\) s\(^{-1}\). The eastern bright source (labeled #2) is a foreground star, while the central source (labeled #1, also known as 1WGA J1713.4−3949) may be associated with the radio pulsar PSR J1713–3949. Discrete regions of extracted spectra, namely the northwestern rim (NW), the southwestern rim (SW) and the northeast rim (NE), are indicated by solid boxes. The central diffuse emission (C) is indicated by a dashed box: flux from the three rims and the two interior point sources were excised from the flux from this region.
2.3. RXTE PCA Observations and Data Reduction

G347.3−0.5 was observed by the RXTE PCA with a pointing position that was offset by 7/8 from the nominal center of the SNR to avoid contaminating flux from three nearby X-ray binaries (4U 1708−408, 1RXS J170849.0−400910, and GPS 1713−388) that appear close to G347.3−0.5 in the sky. Each of these X-ray binaries is located approximately 1° from the pointing position, so none of them appeared within the field of view (1° FWHM) of the RXTE PCA observation. Therefore, effects of contaminating flux from these X-ray binaries can be safely ignored.

The PCA is a spectrophotometer comprising an array of five co-aligned proportional counter units that are mechanically collimated to have a field of view of 1° FWHM. The array is sensitive to photons that have energies between approximately 2 and 60 keV. The energy resolution ΔE/E of the array is 0.18 at 6 keV, and the maximum on-axis collecting area is about 6000 cm² at 9.72 keV. The PCA data were screened to remove the time intervals during which (1) one or more of the five proportional counter units is off, (2) G347.3−0.5 is less than 10° above the limb of the Earth, (3) the background model is not well defined, and (4) the pointing direction of the detectors is more that 0°02 from the nominal pointing direction in either right ascension or declination. After screening the data using these criteria, a final data set was prepared. The PCA background spectrum for G347.3−0.5 was estimated using the FTOOL peabackest.4

G347.3−0.5 lies toward the direction of the Galactic ridge (GR), a region of the Galaxy which features extensive diffuse X-ray emission, as described by Valinia & Marshall (1998). G347.3−0.5 falls within the subregion of the GR denoted as R1 by those authors; for this subregion, Valinia & Marshall (1998) obtained a best fit for the observed X-ray emission using a two-component model. The first component is a Raymond-Smith plasma component, denoted RAYMOND (Raymond & Smith 1977), which describes the emission spectrum from a hot diffuse gas, including line emissions from several elements. Using this model, with abundances frozen to solar, Valinia & Marshall (1998) obtained a photon index of 1.8 for this component. Finally, the derived column density for the thermal component was a simple power law (denoted POWER LAW).

3. SPECTRAL FITTING AND ANALYSIS

3.1. The RXTE Spectrum of G347.3−0.5

After reducing all the data, we proceeded to perform spectral-fitting analysis using the X-ray spectral-fitting package XSPEC,5 first considering the RXTE PCA data. Given that the X-ray emission from G347.3−0.5 is known to be almost entirely nonthermal and probably produced by electrons emitting synchrotron radiation, we used three models for nonthermal X-ray emission to fit the data: a simple power law, the SRESC model, and the SRCUT model. An emission feature is seen in the RXTE PCA spectrum near 6.4 keV; to model this feature, we included a Gaussian component with each of the models used in the spectral fitting (see § 4.3 for a more detailed discussion of this apparent feature).

POWER LAW.—Earlier studies of the X-ray spectra associated with the bright rims of G347.3−0.5 by Koyama et al. (1997) and Slane et al. (1999) revealed that the X-ray emission from the northwestern rim, the southwestern rim, and the eastern region of G347.3−0.5 could all be adequately fitted using a simple power law (with a photon index of ∼2). These fits were made based on ROSAT and ASCA observations (extending to approximately 10 keV), and we performed a fit to the RXTE data using a power law with approximately the same index. We included a second

4 For more information about FTOOLS, see http://heasarc.gsfc.nasa.gov/docs/software/ftools/ftools_menu.html.

5 See http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html for more information about XSPEC.
component, a Gaussian with a line width $\sigma$ frozen to 0 keV, to fit the apparent emission feature seen near 6.4 keV.

Figure 3 shows a POWER LAW+GAUSSIAN fit to the spectrum extracted from the RXTE PCA observations, using an photon index of 2.33 to correspond to the weighted mean value of photon indices obtained in the fits made to the northwestern rim, southwestern rim, and eastern region of G347.3−0.5 by Slane et al. (1999). Clearly, this model did not fit the data in this energy range, yielding a reduced $\chi^2$ of 482. Even when the photon index was a free parameter, an acceptable fit was still not obtained; in Figure 4, we plot the results of a POWER LAW+GAUSSIAN fit where we fit the photon index. In this figure, the photon index is 2.61, yielding a $\chi^2$ of 1808 for 49 degrees of freedom (a reduced $\chi^2$ of 36.9). While this is certainly an improvement, this model still does not fit the data. We conclude that the power-law models employed by Slane et al. (1999) over the energy ranges sampled by ROSAT and ASCA cannot be extended into the RXTE energy range. The energy distribution of the electrons that produce the observed X-ray emission is therefore inconsistent with a simple power law.

SRESC.—The second model used in our analysis was SRESC, which describes a synchrotron spectrum from an electron distribution limited by particle escape above some energy. This model was used by Dyer et al. (2001) to successfully fit the X-ray spectrum of SN 1006, and thorough descriptions of this model are presented by Reynolds (1996, 1998). The SRESC model describes electrons which are shock accelerated in a Sedov blast wave encountering a constant-density medium containing a uniform magnetic field. This model also includes variations in electron acceleration efficiency with shock obliquity and postshock radiative and adiabatic losses.

In Figure 5, we present a fit to the RXTE spectrum using the SRESC model combined with the GAUSSIAN model. Similar to our attempts to fit the spectrum with a POWER LAW+GAUSSIAN model, we could not obtain an acceptable fit to the RXTE spectrum of G347.3−0.5 using this model. For the plotted model, the corresponding ratio of $\chi^2$ to degrees of freedom is 2451/48 = 51.07. We therefore conclude that the SRESC model, like the POWER LAW model, does not properly describe the nonthermal X-ray emission seen from this SNR.

SRCUT.—The third model we considered is denoted as SRCUT, described by Reynolds (1998), Reynolds & Keohane (1999), and Hendrick & Reynolds (2001), with the latter two papers implementing the model in their study of the maximum energies of electrons accelerated by samples
of SNRs in the Galaxy and the Large Magellanic Cloud, respectively. The SRCUT model describes a synchrotron spectrum from a power law distribution (with an exponential cutoff) of electrons in a uniform magnetic field. The photon spectrum is itself a cutoff power law, rolling off more slowly than an exponential in photon energies. Although this model is an oversimplification, it is more realistic than a power law and it does give the maximally curved physically plausible spectrum. This spectrum can in turn be used to set limits on maximum accelerated electron energies even in remnants whose X-rays are thermal. The SRCUT model assumes an electron energy spectrum $N_e(E)$ of the form

$$N_e(E) = KE^{-\Gamma}e^{-E/E_{\text{cutoff}}},$$

where $K$ is a normalization constant derived from the observed flux density of the region of the SNR at 1 GHz, $\Gamma$ is defined as $2\alpha + 1$ (where $\alpha$ is the radio spectral index), and $E_{\text{cutoff}}$ is the maximum energy of the accelerated cosmic-ray electrons. A crucial advantage of this model (as well as the SRESC model) is that a resulting fit can be compared with two observable properties of an SNR, namely, its flux density at 1 GHz and $\alpha$. Finally, one of the fit parameters for the SRCUT and SRESC models is the cutoff frequency $\nu_{\text{cutoff}}$ of the synchrotron spectrum of the electrons. This quantity is defined as the frequency at which the flux has dropped by a factor of 10 from a straight power law. We can express $\nu_{\text{cutoff}}$ in a way that is quantitatively consistent with previous work (Reynolds 1998; Reynolds & Keohane 1999; Hendrick & Reynolds 2001) as

$$\nu_{\text{cutoff}} \approx 1.66 \times 10^{16} \left( \frac{B_{\mu G}}{10 \mu G} \right) \left( \frac{E_{\text{cutoff}}}{10 \text{ TeV}} \right)^2 \text{ Hz},$$

where $B_{\mu G}$ is the magnetic field strength of the SNR in $\mu$G, assuming the electrons are moving perpendicular to the magnetic field. By using the value for $\nu_{\text{cutoff}}$ returned by SRCUT as well as the normalization factor $K$, the synchrotron spectrum of the shock-accelerated electrons can be adequately described. Moreover, an estimate for the maximum energy $E_{\text{cutoff}}$ for the shock-accelerated electrons can also be derived.

In Figure 6, we present a fit to the RXTE spectrum using the SRCUT model. Clearly, this model gives the best fit to the spectrum of G347.3–0.5 over this energy range; the corresponding value for $\chi^2$/degrees of freedom is 207.98/48 = 4.33, which is a considerable improvement (although still not statistically acceptable) over the fits obtained by both the POWER LAW model and the SRESC model. The normalization $K$ for the SRCUT component of this fit indicates that the flux density at 1 GHz for the entire SNR is $6.9 \pm 0.2$ Jy (90% confidence limits). This value is marginally consistent with the weak radio emission seen from this SNR, known to be dominated by a source of emission at the northwestern rim of G347.3–0.5 with a corresponding flux density of $4 \pm 1$ Jy (Ellison et al. 2001). Moreover, the broad field of view of the PCA certainly intercepts diffuse X-ray flux from other sources besides G347.3–0.5, which leads to a corresponding increase in the value for $K$ returned by the fit. We also note that by using the best-fit value for $\nu_{\text{cutoff}}$, equation (2) yields $E_{\text{cutoff}} \approx 36$ TeV (assuming a magnetic field strength of 10 $\mu$G). This is in good agreement with the value of $E_{\text{cutoff}}$ obtained by Ellison et al. (2001) using a similar value for $B_{\mu G}$ with different models. Based on our success in fitting the RXTE spectrum of G347.3–0.5 with the SRCUT model, we conclude that the energy distribution of the highest energy cosmic-ray electrons accelerated by this SNR is consistent with a power law that features an exponential cutoff.

### 3.2. Joint Spectral Fitting of ROSAT PSPC, ASCA GIS, and RXTE PCA Data

We next applied the SRCUT model to the X-ray spectrum of G347.3–0.5 as observed by the ROSAT PSPC and the ASCA GIS as well as the RXTE PCA. We took advantage of the spatial resolving capabilities of the ROSAT PSPC and the ASCA GIS in order to simultaneously fit spectra extracted from particular regions of the SNR. We simultaneously fit eight different X-ray spectra: the spectra for the northwestern rim, the southwestern rim, the northeastern rim, and the diffuse central emission (with the two interior point sources omitted) as observed by the ROSAT PSPC, the spectra for the northwestern rim, the southwestern rim, and the northeastern rim as observed by the ASCA GIS, and finally the spectra for the whole SNR as observed by the RXTE PCA. In all cases, photoelectric absorption along the line of sight was modeled using the Wisconsin (Morrison & McCammon 1983) cross sections and relative abundances of elements as described by Anders & Ebihara (1982).

Two models (each a combination of a thermal component and a nonthermal component) were used for the joint spectral-fitting process—namely, a RAYMOND+SRCUT model and an EQUIL+SRCUT model—in order to fit both the thermal and nonthermal components, respectively, in the individual spectra. In their study of the X-ray spectrum of G347.3–0.5 based on ROSAT PSPC and ASCA GIS data, Slane et al. (1999) found no evidence for thermal emission from any portion of the SNR. We revisited this issue by testing whether the joint fit to the individual spectra would be improved by the inclusion of a thermal component. Both thermal models describe the emission spectrum from a hot
diffuse gas, including line emission from several elements, that is in a state of collisional ionization equilibrium. Both of these models have a common set of parameters: a plasma temperature $kT$, an abundance $Z$, a redshift $z$, and an emission measure $EM$. For the purposes of the present work, we froze the values of $Z$ and $z$ to unity (i.e., solar abundance) and zero, respectively. The emission measure $EM$ is defined as

$$EM (cm^{-5}) = \frac{10^{-14}}{4\pi d^2} \int n_\text{e} n_\text{H} \, dV,$$

where $d$ is the distance to the source in centimeters, and $n_\text{e}$ and $n_\text{H}$ are the electron and hydrogen densities, respectively, in units of cm$^{-3}$. We can evaluate this expression as follows: we recall that we have assumed a distance of 6 kpc to G347.3−0.5 and we note that the angular size of this SNR is $65' \times 55'$ (Green 2001); therefore the corresponding linear radius is $1.65 \times 10^{20}$ cm. Assuming a spherical volume for the SNR with a filling factor of one-quarter (that is, assumed only one-quarter of the total volume of the SNR is filled with thermal particles that produce the observed emission), as well as uniform values for $n_\text{e}$ and $n_\text{H}$ throughout the volume, then equation (3) yields

$$EM (cm^{-5}) = \left(\frac{10^{-14}}{4\pi d^2}\right) \left(\frac{4}{3}\pi r^3\right) n_\text{e} n_\text{H} = (10.92 \text{ cm}) n_\text{e} n_\text{H} .$$

We can estimate the ambient densities of hydrogen surrounding G347.3−0.5 from the values obtained from the spectral fits for EM (assuming $n_\text{e} = 1.2 n_\text{H}$). We will continue this discussion when we describe our detection of thermal X-ray emission from G347.3−0.5 in §4.2.

We have modeled the background diffuse X-ray emission from the GR as observed by the RXTE PCA with the same two-component model used by Valinia & Marshall (1998) mentioned earlier, namely a RAYMOND+POWER LAW model where the abundance $Z$ is frozen to solar values and the redshift $z$ is frozen to zero. We froze the values for $kT$, photon index, and $N_\text{H}$ to be $2.9$ keV, 1.8, and $1.8 \times 10^{22}$ cm$^{-2}$, respectively; these are the same best-fit values measured by Valinia & Marshall (1998). The normalizations for the RAYMOND and POWER LAW components were left as free parameters.

In Figures 7, 8, and 9, we present data, fits, and residuals for the spectra extracted from the ROSAT PSPC regions (Fig. 7), the ASCA GIS regions (Fig. 8), and the whole SNR as observed by the RXTE PCA (Fig. 9) using the RAYMOND+SRCUT model. Similarly, in Figures 10, 11, and 12, we present data, fits, and residuals for the same set of spectra using the EQUIL+SRCUT model. In Tables 2 and 3, we present the fit parameters for the depicted fits; the quality of the two fits is comparable for the two models ($\chi^2$/degrees of freedom of 808.25/471 = 1.72 for the RAYMOND+SRCUT model compared to a $\chi^2$/degrees of freedom of 843.76/472 = 1.79 for the EQUIL+SRCUT model for 501 pulse height amplitude bins). We emphasize that, for both two-component models, the fits successfully reproduce the observed radio properties of G347.3−0.5, namely, the two estimates for the flux densities at 1 GHz for the northwestern rim are both consistent with the observed value of 4 ± 1 Jy (Ellison et al. 2001). In addition, the estimates for the flux densities at that frequency for the other portions of the SNR are very modest, also consistent with observations. In the next section we discuss these fit parameters in more detail.

4. RESULTS

4.1. Cutoff Energies of Electrons Shock-Accelerated by G347.3−0.5

The electron energy $E_\text{e}$ associated with synchrotron photons radiated at energy $E_\text{X}$ is given by the relation

$$E_\text{e} \approx \frac{120 \text{ TeV}}{B_{\mu G}^{1/2}} \left(\frac{E_\text{X}}{1 \text{ keV}}\right)^{1/2} .$$

We can use this equation and the values for $\nu_{\text{cutoff}}$ derived by our fits to estimate the maximum energy $E_{\text{cutoff}}$ of the electrons accelerated by G347.3−0.5. We took four values for $\nu_{\text{cutoff}}$ yielded by our fits to the emission from the northwestern rim and the diffuse central emission using the

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6 The Catalogue of Galactic Supernova Remnants (Green 2001) is also available at http://www.mrao.cam.ac.uk/surveys/snr.
SRCUT+RAYMOND model and the SRCUT+EQUIL model. Using equation (5), \( E_{\text{X}} = \frac{\hbar}{C^2 \alpha_2} \) cutoff yields an estimate for \( E_{\text{cutoff}} \) (assuming a magnetic field of 10 \( \mu \)G), and we list our calculated values for \( E_{\text{cutoff}} \) in Table 4. These values range from approximately 36 to 48 TeV and are slightly greater than the values presented by Ellison et al. (2001). We agree with the results and arguments of Slane et al. (1999) and Ellison et al. (2001) that G347.3/C0.5 is not accelerating cosmic-ray electrons to the knee energy of 3000 TeV. In \( \S \) 5, we describe a more rigorous attempt to estimate the maximum energy of cosmic-ray electrons accelerated by this SNR, where we simultaneously consider radio, X-ray, and TeV emission from the northwestern rim. There we employ a more sophisticated fitting method in which the ambient magnetic field strength is allowed to vary.

4.2. Thermal X-Ray Emission from G347.3—0.5?

Previous X-ray observations of G347.3—0.5 by Koyama et al. (1997) and Slane et al. (1999) found no evidence for thermal emission from any portion of this SNR. Slane et al. (1999) placed upper limits on the amount of thermal emission as a function of \( kT \) for both emission from the northwestern rim and the central diffuse emission of G347.3—0.5. By including a thermal component in fits to the X-ray emission from G347.3—0.5, we reexamine the upper limits on thermal emission derived by Slane et al. (1999).

In Table 4, we present values for \( E_{\text{cutoff}} \), \( \Gamma \), \( n_{\text{H}} \), and \( n_e = 1.2 n_{\text{H}} \), as calculated from our model fit values for \( \alpha \), EM, and equation (4). We have considered only the fit values for the northwestern rim and the central diffuse emission.
based on the results of both the SRCUT+RAYMOND model and the SRCUT+EQUIL model. For the northwestern rim, we can only provide upper limits for \( n_\text{H} \) and \( n_\text{e} \). In Figures 13 and 14, we plot our values for EM for the northwestern rim and the central diffuse emission, respectively, against the upper limits derived by Slane et al. (1999). We find that for the northwestern rim, our values for EM fall well below the upper limits of Slane et al. (1999), but for the diffuse emission form the central region, our values for EM more closely straddle the upper limits, and in the case of SRCUT+RAYMOND our value exceeds the upper limit. This result indicates the first detection of thermal X-ray emission from G347.3–0.5; we speculate that earlier work may have missed this thermal emission because earlier efforts concentrated on the nonthermal properties of this SNR (particularly the bright rims of this SNR) and only considered a narrower energy range of the spectrum of G347.3–0.5. In addition, the rather large angular size of this SNR makes it difficult to completely sample all of its X-ray properties. A more thorough understanding of the rather modest thermal emission from this SNR will require additional observations and modeling.

4.3. The Detection of Iron Emission: Galactic Ridge Background?

We now comment on a modest spectral feature seen near 6.4 keV in the RXTE PCA spectrum of G347.3–0.5 and at a similar energy in the spectra from the two background observations also made with the RXTE PCA. This emission feature may be associated with iron, which is known to produce a broad set of emission features between the energies of 6 and 7 keV. One possibility to consider is that the feature is produced by thermal emission from G347.3–0.5; we note that Bykov (2002) has recently argued that fast-moving isolated fragments of SN ejecta composed of heavy elements (such as iron) should produce K\( \alpha \) fluorescence emission lines at X-ray energies, and that the iron K\( \alpha \) fluorescence emission line energy is known to be approximately 6.4 keV. A second possibility is that the feature originates from diffuse emission associated with the GR, which is seen in projection beyond G347.3–0.5. The large field of view of the RXTE PCA (approximately 1° FWHM) and the lack of imaging capabilities of this instrument make it difficult to clearly associate this feature with either G347.3–0.5 or the GR. Recently, Tanaka (2002) presented an analysis of spectral features, including the iron K\( \alpha \) fluorescence emission line, associated with different portions of the GR, as observed by the ASCA SIS.

In Table 5, we present the line energies and normalizations (along with the 90% confidence limits for these values) for the emission feature as seen in the RXTE PCA spectra of G347.3–0.5 and the two background pointings. We also performed a simultaneous fit of the emission feature as seen in the three spectra, where the line energies and the normalizations for the feature as seen in each spectra were fixed to be the same. We also present in Table 5 the best-fit values for the line energy and the normalization for the joint fit as well. Note that in each case, the line energies and the normalizations are all approximately the same, within the confidence limits. In order to check for any instrumental effects that may be corrupting the data, we obtained archived data from an RXTE PCA observation of Cas A made on 1999 August 5 (ObsID 40806–01–04–00); we selected this particular observation of Cas A for analysis because it took place nearly contemporaneously to our G347.3–0.5 observation (less than 2 months later). Using the same data-reduction techniques described in § 2.3, we generated a

![Fig. 11. Spectra of the northwestern rim (NW), the southwestern rim (SW), and the northeastern rim (NE) of G347.3–0.5 as observed by the ASCA GIS and fit using the EQUIL+SRCUT model.](image1)

![Fig. 12. Spectrum of G347.3–0.5 as observed by the RXTE PCA and fit using the EQUIL+SRCUT model.](image2)
source spectrum of Cas A and measured both the line energy and the normalization of the iron Kα emission line seen in the spectrum of Cas A. We measured a line energy of 6.66 ± 0.02 keV, which is in good agreement with the energy of this emission line in the ASCA GIS spectra of Cas A as observed by Holt et al. (1994). Thus, we conclude that there are no instrumental effects that are corrupting our analysis of the emission feature near 6.4 keV.

We therefore hypothesize that the spectral feature seen in the RXTE PCA is not associated with G347.3−0.5, for two major reasons. First, this feature was not detected either by Slane et al. (1999) or by us during the analysis of ASCA GIS observations of this SNR that sampled the energy range including this spectral feature. Second, by inspection of Figure 2 and Table 5, it is clear that the emission feature is seen in both the on-source RXTE PCA pointing and the two background pointings, and the line energies and normalizations of the emission features for all three pointings are similar. If this feature were associated with G347.3−0.5 rather than the GR, we would expect that the line energy and/or the normalization in the source region would significantly differ from the values seen for the feature in the two background pointings. In the study of spectral features observed from diffuse X-ray emission from the GR, Tanaka (2002) found that only diffuse emission from within 1° of the Galactic center exhibited a feature near 6.7 keV, while the diffuse line spectrum from two other regions, centered at longitudes of 10° and 28°5, respectively, were dominated instead by a feature near 6.7 keV. Because neither of these two regions include the positions of G347.3−0.5 or the two background regions, however, we argue that the results from Tanaka (2002) are not applicable to our study presented here. We therefore conclude that the spectral feature is not associated with G347.3−0.5 and instead originates in

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**TABLE 2**

| Model          | Parameter | Value       | 90% Confidence Limits |
|----------------|-----------|-------------|-----------------------|
| NW Region      |           |             |                       |
| WABS           | NH        | 0.74 × 10^{22} cm^{-2} | 0.71, 0.77 |
| SRCUT          | α         | 0.55        | 0.51, 0.59            |
|                | ν_{cutoff} | 5.00 × 10^{17} Hz | 4.76, 5.48 |
|                | Normalization K | 4.02 Jy   | 3.89, 4.09            |
| RAYMONDA       | kT        | 1.15 keV    | ...                  |
|                | Emission measure (EM) | ≤4.54 × 10^{-3} cm^{-3} | ... |
| NE Region      |           |             |                       |
| WABS           | NH        | 0.61 × 10^{22} cm^{-2} | 0.45, 0.76 |
| SRCUT          | α         | 0.37        | 0.34, 0.52            |
|                | ν_{cutoff} | 9.21 × 10^{17} Hz | 8.28, 10.21 |
|                | Normalization | 4.07 × 10^{-2} Jy | 1.38 × 10^{-3}, 0.11 |
| RAYMONDA       | kT        | 1.15 keV    | 0.99, 1.71            |
|                | Emission measure (EM) | 6.11 × 10^{-3} cm^{-3} | 3.05 × 10^{-3}, 9.69 × 10^{-3} |
| SW Region      |           |             |                       |
| WABS           | NH        | 0.63 × 10^{22} cm^{-2} | 0.60, 0.65 |
| SRCUT          | α         | 0.50        | 0.48, 0.53            |
|                | ν_{cutoff} | 8.38 × 10^{17} Hz | 7.83, 8.97 |
|                | Normalization | 0.72 Jy   | 0.43, 0.92            |
| RAYMONDA       | kT        | 3.31 keV    | 2.82, 4.00            |
|                | Emission measure (EM) | 3.66 × 10^{-3} cm^{-3} | 2.63 × 10^{-3}, 4.78 × 10^{-3} |
| Center Region  |           |             |                       |
| WABS           | NH        | 0.49 × 10^{22} cm^{-2} | 0.47, 0.51 |
| SRCUT          | α         | 0.48        | 0.47, 0.51            |
|                | ν_{cutoff} | 8.31 × 10^{17} Hz | 7.90, 8.69 |
|                | Normalization | 1.28 Jy   | 0.98, 1.30            |
| RAYMONDA       | kT        | 1.56 keV    | 1.50, 1.61            |
|                | Emission measure (EM) | 3.85 × 10^{-2} cm^{-3} | 3.65 × 10^{-2}, 4.15 × 10^{-2} |
| Background     |           |             |                       |
| WABS           | NH        | 1.8 × 10^{22} cm^{-2} | ... |
| POWER LAW      | Photon index | 1.8        | ...                  |
|                | Normalization | 2.72 × 10^{-3} photons keV^{-1} cm^{-2} s^{-1} at 1 keV | 2.57 × 10^{-3}, 2.84 × 10^{-3} |
| RAYMONDA       | kT        | 2.9 keV     | ...                  |
|                | Emission measure (EM) | 3.46 × 10^{-2} cm^{-3} | 3.38 × 10^{-2}, 3.55 × 10^{-2} |

**Note.**—χ^2/degrees of freedom = 808.25/471 = 1.72 using 501 PHA bins.

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a Abundance frozen at 1.0 and redshift frozen at 0.0.
b See § 3.2.
c Galactic diffuse background as observed by the RXTE PCA over the energy range of 2 through 30 keV. NH, photon index and kT have all been frozen to the values measured by Valinia & Marshall 1998.
X-ray source centrally located inside G347.3–0.5 by Crawford et al. (2002) discovered a new pulsar (PSR J1713–0.5) near the center of G347.3–0.5. In addition, the position of G347.3–0.5 suggests that the X-ray source (as well as the radio pulsar) and the SNR are associated. In addition, the position of G347.3–0.5 itself near a molecular cloud also suggests that the SNR was produced by a massive star in a core-collapse SN; these types of SNe are expected to produce neutron stars. To further investigate the nature of 1WGA J1713.4–3949, we performed a timing analysis of our RXTE PCA data to search for pulsations from this source.

In Figure 15, we present a power spectrum of our PCA data over the frequency range of 2–30 keV. We find no evidence for pulsations in our spectrum at any frequency, including 2.55 Hz. Our failure to detect pulsations from this source may be explained by several factors, such as significant contaminating diffuse background emission from the GR, cosmic ray background, and finally emission from the SNR dominating over emission from a pulsar over the energy range sampled by our RXTE PCA observation. Pointed high angular resolution X-ray

### Table 3

| Model     | Parameter | Value             | 90% Confidence Limits |
|-----------|-----------|-------------------|-----------------------|
| NW Region |           |                   |                       |
| WABS      | $N_H$     | $0.74 \times 10^{22}$ cm$^{-2}$ | 0.70, 0.79            |
| SRCUT     | $\alpha$  | 0.55              | 0.49, 0.57            |
|           | $\nu_{\text{cutoff}}$ | $5.07 \times 10^{17}$ Hz | 4.52, 5.10            |
|           | Normalization | 4.48 Jy | 2.70, 4.55            |
| EQUIL$^a$ | $kT$      | 0.49 keV          |                       |
|           | Emission measure (EM)$^b$ | $\leq 6.4 \times 10^{-3}$ cm$^{-3}$ | ... |
| NE Region |           |                   |                       |
| WABS      | $N_H$     | $0.66 \times 10^{22}$ cm$^{-2}$ | 0.56, 0.75            |
| SRCUT     | $\alpha$  | 0.44              | 0.37, 0.50            |
|           | $\nu_{\text{cutoff}}$ | $10.10 \times 10^{17}$ Hz | 8.93, 12.00           |
|           | Normalization | 0.14 Jy | 0.03, 0.51            |
| EQUIL$^a$ | $kT$      | 1.34 keV          | 1.08, 1.71            |
|           | Emission measure (EM)$^b$ | $9.31 \times 10^{-3}$ cm$^{-3}$ | 6.56 $\times 10^{-2}$, 1.31 $\times 10^{-2}$ |
| SW Region |           |                   |                       |
| WABS      | $N_H$     | $0.61 \times 10^{22}$ cm$^{-2}$ | 0.58, 0.69            |
| SRCUT     | $\alpha$  | 0.52              | 0.49, 0.55            |
|           | $\nu_{\text{cutoff}}$ | $8.52 \times 10^{17}$ Hz | 7.97, 8.93            |
|           | Normalization | 1.10 Jy | 0.58, 1.74            |
| EQUIL$^a$ | $kT$      | 1.31 keV          |                       |
|           | Emission measure (EM)$^b$ | $\leq 2.5 \times 10^{-3}$ cm$^{-3}$ | ... |
| Center Region |           |                   |                       |
| WABS      | $N_H$     | $0.49 \times 10^{22}$ cm$^{-2}$ | 0.48, 0.51            |
| SRCUT     | $\alpha$  | 0.50              | 0.49, 0.52            |
|           | $\nu_{\text{cutoff}}$ | $8.41 \times 10^{17}$ Hz | 8.07, 8.72            |
|           | Normalization | 1.94 Jy | 1.42, 2.61            |
| EQUIL$^a$ | $kT$      | 1.69 keV          | 1.62, 1.74            |
|           | Emission measure (EM)$^b$ | $3.61 \times 10^{-2}$ cm$^{-3}$ | 3.45 $\times 10^{-2}$, 3.82 $\times 10^{-2}$ |
| Background$^a$ |           |                   |                       |
| WABS      | $N_H$     | $1.8 \times 10^{22}$ cm$^{-2}$ | ... |
| POWER LAW | Photon index$^c$ | 1.8 | ... |
|           | Normalization | $3.07 \times 10^{-3}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV | $2.91 \times 10^{-3}$, 3.18 $\times 10^{-3}$ |
| RAYMONDa  | $kT$      | 2.9 keV           | ... |
|           | Emission measure (EM)$^b$ | $3.11 \times 10^{-2}$ cm$^{-3}$ | $3.04 \times 10^{-2}$, 3.21 $\times 10^{-2}$ |

Note.—$\chi^2$/degrees of freedom = 843.76/472 = 1.79 using 501 PHA bins.

$^a$ Abundance frozen at 1.0 and redshift frozen at 0.0.

$^b$ See § 3.2.

$^c$ Galactic diffuse background as observed by the RXTE PCA over the energy range of 2–30 keV. $N_H$, photon index, and $kT$ have all been frozen to the values measured by Valinia & Marshall 1998.

#### 4.4. X-Ray Pulsations from the Radio Pulsar PSR J1713–3949 (Possibly Associated with 1WGA J1713.4–3949 and G347.3–0.5)$^a$

Recent radio observations of 1WGA J1713.4–3949 (the X-ray source centrally located inside G347.3–0.5) by Crawford et al. (2002) discovered a new pulsar (PSR J1713–3949) with a period of 392 ms within 7" (the discovery beam radius) of the X-ray source. Crawford et al. (2002) derived a distance of 5.0 ± 0.2 kpc to this source, which is consistent with the distance estimate to G347.3–0.5 of Slane et al. (1999). The position of 1WGA J1713.4–3949 near the center of G347.3–0.5 suggests that the X-ray source (as well as the radio pulsar) and the SNR are associated. In addition, the position of G347.3–0.5 itself near a...
observations of this source will be much more sensitive to pulsed X-ray emission, if it exists.

5. THE BROADBAND ENERGY SPECTRUM OF THE NORTHWESTERN RIM OF G347.3–0.5

In Figure 16, we present a broadband energy spectrum of the northwestern rim of G347.3–0.5 ranging from radio through γ-ray energies. We have constructed this diagram using published values for the 1 GHz radio observation of G347.3–0.5 by the Australian Telescope Compact Array (ATCA) as presented by Ellison et al. (2001), the ROSAT PSPC and ASCA GIS data described previously in this paper, and data from the CANGAROO observation at TeV energies of the spectrum of this rim as published by Enomoto et al. (2002). Using the ISIS software package7 (Houck & Denicola 2000), we obtained a fit to the energy spectrum using a model that includes multiple high-energy processes associated with SNRs, as indicated by separate curves. These curves indicate the emission profile expected by a shock-accelerated population of electrons from two different processes: synchrotron emission (as indicated by the curve labeled “S”), and inverse-Compton emission from cosmic microwave background photons that have been upscattered to TeV energies by energetic cosmic-ray electrons (the curve labeled “IC”). These emission models are consistent with the models employed by Sturner et al. (1997), and a detailed discussion of the high-energy emission from nonlinear shock acceleration processes associated with SNRs is given by Baring et al. (1999). From our fit to the ASCA GIS data and the TeV data, we have derived estimates for $E_{\text{cutoff}}$ of the accelerated cosmic-ray electrons and magnetic field strength $B$. For the depicted fit, the $\chi^2$/degree of freedom is 191:78/113 = 1.70. Based on this fit, we estimate a value of only $8.8_{-3.3}^{+4.1}$ TeV for $E_{\text{cutoff}}$ of the accelerated cosmic-ray electrons and a corresponding magnetic field strength of $B = 150_{-80}^{+250}$ μG. This value for $E_{\text{cutoff}}$ is sharply lower (but still consistent) with the upper limit derived by Ellison et al. (2001), while the corresponding value for $B$ is considerably larger than the value of 10 μG assumed by Slane et al. (1999). There is also a modest amount of overlap between our range of values for $B$ and the range suggested by Enomoto et al. (2002) (10–100 μG).

Fig. 13.—Upper limits on emission measure for the northwestern rim of G347.3–0.5, as calculated by Slane et al. (1999). The values (corresponding to 90% confidence limits) for the emission measure from our fits to the northwestern rim using the RAYMOND+SRCUT and EQUIL+SRCUT are plotted by a diamond and a square, respectively.

Fig. 14.—Estimates of the emission measure for the central diffuse emission from G347.3–0.5, as calculated by Slane et al. (1999). The values (with 90% confidence intervals) for the emission measure from our fits to the northwestern rim using the RAYMOND+SRCUT and EQUIL+SRCUT are plotted by a diamond and a square, respectively.

7 See http://space.mit.edu/ASC/ISIC for more information about ISIS.
we allowed this ratio to vary and obtained a value of $V_{\text{TeV}} / V_{\text{X-ray}} \approx 1000$, with a lower limit of 360, assuming that the power-law index is 2.1 (derived from our model fits where $\alpha = 0.55$) and that there is no curvature to the electron spectrum. This ratio is too high to be physically acceptable, and suggests that the TeV emission from the northwestern rim of G347.3–0.5 is not produced by inverse Compton scattering of cosmic microwave background photons off high-energy electrons accelerated along this rim of the SNR.

Nonetheless, while this TeV emission may not be produced by inverse Compton scattering, we argue that neutral pion decay also cannot produce this emission. We point out that in arguing that the TeV emission is produced by neutral pion decay, Enomoto et al. (2002) assumed an extremely large ambient density ($n \approx 100 \, \text{cm}^{-3}$ if a distance of 6 kpc to G347.3–0.5 is assumed) for the northwestern rim of the SNR. Our fits to the thermal component of the X-ray emission from the northwestern rim and the central diffuse emission yield a dramatically lower ambient density ($n \approx 0.05$–0.07 cm$^{-3}$) and make the conclusions of Enomoto et al. (2002) seem untenable. Slane et al. (1999) also concluded that G347.3–0.5 is expanding into an ambient interstellar medium with an extremely low density, and suggested that the SNR is expanding into the evacuated wind-blown cavity created by the stellar progenitor; we agree with this finding, and suggest that while G347.3–0.5 may have formed in the vicinity of dense molecular clouds, it has not yet begun to interact with these clouds. We also note that the observed TeV emission is observed to be centered on the northwestern rim of the SNR and not on the adjacent cloud, as assumed by Enomoto et al. (2002). Finally, Reimer & Pohl (2002) noted that the flux of the GeV emission from the $\gamma$-ray source 3EG J1714–3857 can be used to constrain the neutral pion decay spectrum fit presented by Enomoto et al. (2002); if this source is associated with the northwestern rim of G347.3–0.5, its flux must be taken into account in all spectral fits, while if the $\gamma$-ray source is not associated with this rim, then the GeV emission can be treated instead as upper limits on flux along this energy range. Reimer & Pohl (2002) showed that the flux from the neutral pion decay spectrum fit exceeded the observed GeV emission by a factor of 3, therefore strongly arguing against neutral pion decay as the process responsible for the TeV emission. For these reasons, we argue that the TeV emission observed from the northwestern rim of G347.3–0.5 is not produced by neutral pion decay. We also comment that if the ambient density is as low as inferred by our estimates, the process of nonthermal bremsstrahlung

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**TABLE 5**

| Pointing               | Line Energy (keV) | 90% Confidence Limits | Normalization (10$^{-4}$ photons cm$^{-2}$ s$^{-1}$) | 90% Confidence Limits |
|------------------------|-------------------|------------------------|---------------------------------------------------|-----------------------|
| G347.3–0.5.............. | 6.41              | 6.38, 6.42             | 5.05                                              | 4.70, 5.40             |
| Background 1............ | 6.51              | 6.47, 6.56             | 4.80                                              | 4.11, 5.59             |
| Background 2............ | 6.26              | 6.13, 6.37             | 7.24                                              | 5.48, 9.91             |
| Joint fit..............  | 6.43              | 6.40, 6.45             | 5.06                                              | 4.76, 5.38             |
| Cas A.................   | 6.66              | 6.64, 6.67             | 58.4                                              | 57.8, 59.2             |

*See § 4.3.*

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![Fig. 15](image1.png)

**Fig. 15.**—Power spectrum of RXTE PCA observation of G347.3–0.5. The frequency corresponding to the putative pulsar (392 ms or 2.55 Hz) is indicated by the vertical dashed line. No evidence for pulsations is detected at this frequency.

![Fig. 16](image2.png)

**Fig. 16.**—Radio to $\gamma$-ray photon energy-flux spectrum of the northwestern rim of G347.3–0.5. See § 5.
emission—as well as neutral pion decay—will be significantly suppressed. A nonthermal bremsstrahlung origin for the TeV emission may also be ruled out because a spectrum generated by this process would, like the spectrum produced by neutral pion decay, exceed the observed GeV emission. In conclusion, we state that none of the known high-energy processes associated with SNRs—inverse Compton scattering, neutral pion decay, and nonthermal bremsstrahlung—can adequately fit the observed TeV emission from the northwestern rim of G347.3. From the work of Ellison, Berezhko, & Baring (2000), we suspect that all models of high-energy emission from SNRs over broad energy ranges must take into account some curvature in the energy spectrum of accelerated electrons rather than assuming simple power laws. In such a case, one of these emission processes may be able to adequately fit the observed TeV emission from the northwestern rim of G347.3—0.5, and perhaps the rims of other SNRs detected at such high energies, after all. We will discuss such curvature in the energy spectra of SNRs in more detail in a future work.

Finally, we consider the putative association between G347.3—0.5 and the X-ray source AX J1714.1—3912, a hard-spectrum source coincident with a molecular cloud located along the northeastern rim of G347.3—0.5. Uchiyama et al. (2003) presented an analysis of the spectral properties of this source using data from ASCA GIS observations. The X-ray spectrum of this source was best fit by a power law with a rather flat photon index of $\Gamma = 1.0^{+0.4}_{-0.3}$, prompting Uchiyama et al. (2003) to argue that such a spectrum was best interpreted as nonthermal bremsstrahlung emission from particles accelerated at the shock interface between the northeastern rim of G347.3—0.5 and the molecular cloud. Despite the spatial proximity between G347.3—0.5 and the molecular cloud (and, by extension, AX J1714.1—3912), the evidence for the association between these sources is not compelling because, based on simulations of the interactions between SNRs and interstellar clouds (Jun & Jones 1999), we expect the amount of radio emission from both the SNR and the cloud to dramatically increase as a result of the interaction. Jun & Jones (1999) also predict that if the SNR has overtaken the cloud, the radio emission from the SNR would “wrap around” the cloud, and such a morphology should be readily apparent. An example of a wrap-around morphology is seen along the interface between the SNR Puppis A and an adjacent molecular cloud (K. Flanagan 2002, private communication). Radio images of G347.3—0.5 and its surrounding environment have been made with the Molonglo Observatory Synthesis Telescope (MOST) (Roberts 1994) and presented by Slane et al. (1999) (at the frequency of 843 MHz) and Ellison et al. (2001) (at the frequency of 1.4 GHz). Inspection of these images reveals little (if any) radio emission at either the position of AX J1714.1—3912 or the northeastern rim of G347.3—0.5, and no evidence for a “wrap-around” morphology in the radio emission. The failure to detect radio emission from the hard X-ray source or the northeastern rim of the SNR and a wrap-around morphology to the radio emission argues against an interaction taking place at that site. Another reason to doubt that an interaction is taking place between G347.3—0.5 and the molecular cloud is related to the ratio of emission from rotational transitions of CO molecules, $\text{CO}(J = 2 \rightarrow 1)/\text{CO}(J = 1 \rightarrow 0)$, as measured at the site of the cloud. An enhanced value for this ratio (such as a value of 1.2 or greater) is thought to indicate that an interaction is taking place between the cloud and a shock, such as the one associated with an SNR (Seta et al. 1998). Both Slane et al. (1999) and Butt et al. (2001) found an enhanced value for this ratio for the cloud along the northeastern rim of the SNR, but we suggest that in this particular case the enhanced $\text{CO}(J = 2 \rightarrow 1)/\text{CO}(J = 1 \rightarrow 0)$ ratio and the low ambient density of the SNR cannot be reconciled, and that (as mentioned before) G347.3—0.5 is not currently interacting with this molecular cloud. Butt et al. (2001) measured a value for the flux ratio $\text{CO}(J = 2 \rightarrow 1)/\text{CO}(J = 1 \rightarrow 0)$ of 2.4 $\pm$ 0.9; according to Draine & Roberge (1984), such a flux ratio corresponds to a shock velocity of less than 5 km s$^{-1}$ in the cloud. The shock speed in a cloud is reduced by the square root of the ratio of the ambient densities. Based on CO observations (Bronfman et al. 1989; Butt et al. 2001), the mean density of the cloud has been estimated to be approximately 500 cm$^{-3}$. From our spectral fits, we have inferred an average ambient density G347.3—0.5 to be $\leq$0.06 cm$^{-3}$; from these estimates for the mean density of the cloud and ambient density around the SNR, we conclude that the shock velocity outside the cloud is less than 500 km s$^{-1}$. For comparison, if we assume that the electrons and protons in G347.3—0.5 are in thermal equilibrium at $kT = 1.5$ keV (from our fits to the diffuse thermal emission from the SNR), then the corresponding shock velocity is approximately 1100 km s$^{-1}$. Since the proton temperature is most likely much larger than the electron temperature in the case of young SNRs (Hwang et al. 2002), like G347.3—0.5, this value for the shock velocity is actually a lower limit, and therefore the shock velocity exceeds 1100 km s$^{-1}$, which is in sharp disagreement with the shock velocity of less than 500 km s$^{-1}$ derived earlier. Uchiyama et al. (2003) noted that the large X-ray luminosity of AX J1714.1—3912 ($1.7 \times 10^{35}$ ergs s$^{-1}$ at the assumed distance of 6 kpc) made G347.3—0.5 barely able to provide enough kinetic energy (in the form of nonthermal particles) to power this source, unless G347.3—0.5 is much closer than 6 kpc or the SN explosion that created this SNR had more kinetic energy (in the form of nonthermal particles) to 6. COMPARISON WITH OTHER SHELL-TYPE SNRs WITH NONTHERMAL X-RAY EMISSION: SN 1006 AND G266.2—1.2

In Table 6, we compare the gross properties of G347.3—0.5 with two other dynamically young shell-type SNRs that possess significant nonthermal components to their X-ray emission, SN 1006 (Dyer et al. 2001; Allen et al. 2001) and G266.2—1.2 (Slane et al. 2001). Inspection of Table 6 reveals that all three SNRs are X-ray luminous, radio faint, and are expanding into regions of the interstellar medium with particularly low ambient density. Both core-collapse and Type Ia SNe appear to produce SNRs with nonthermal X-ray emission; SN 1006 is the archetype of a SNR produced by a Type Ia SN, while G266.2—1.2 and G347.3—0.5 are thought to be produced by Type II SNe. The X-ray morphologies of these three SNRs contrast as well: for SN 1006, the morphology is bilateral with two X-ray bright rims, visible in ASCA images of this SNR;
(Dyer et al. 2001), while the morphologies of both G266.2–1.2 and G347.3–0.5 feature multiple bright rims; ROSAT and ASCA images of these two SNRs reveal luminous northwestern, southwestern, and northeastern rims for both SNRs, while G266.2–1.2 has a luminous southern rim as well (Slane et al. 1999, 2001). The X-ray synchrotron flux depends on the exponential cutoff energy, the strength of the magnetic field, and the density of nonthermal electrons. In the case of SN 1006, the morphology may be due to an enhancement (via compression) in the magnetic field along the two bright rims relative to the magnetic field strength elsewhere along the rim. The morphology of SN 1006, with two symmetric luminous X-ray rims, was reproduced remarkably well by the work of Reynolds (1998), who described models of synchrotron X-rays from shell supernova remnants. In the cases of G347.3–0.5 and G266.2–1.2, the cause of the morphology is not clear. The bright rims may be associated with regions where the density of nonthermal electrons is relatively high. The common property of low ambient density for these SNRs does not imply an exclusive requirement for nonthermal X-ray emission; for example, another SNR, Cas A, possesses a strong nonthermal X-ray component to its emission (Vink & Laming 2003), although not a component that dominates the X-ray spectrum of the SNR, and is expanding into a particularly dense ambient medium. Nonetheless, it appears that a low ambient density, independent of the type of SN progenitor, is conducive to the X-ray spectrum of the SNR being dominated by nonthermal X-ray emission. Deep X-ray observations and detailed analysis of other SNRs located in regions of low ambient density are required to determine the degree to which low ambient density is necessary for producing this type of X-ray emission; we will explore this subject in more detail using a sample of such SNRs in a future work.

7. CONCLUSIONS

The results and conclusions of this work may be summarized as follows.

1. We present a spatially resolved X-ray spectral analysis of both the three bright rims and the diffuse central emission of the Galactic SNR G347.3–0.5. This analysis involves data from observations made of this source using instruments aboard three different X-ray satellites (the ROSAT PSPC, the ASCA GIS, and the RXTE PCA) spanning the approximate energy range of 0.5–30 keV.

2. We have successfully fitted the spatially resolved X-ray spectra of G347.3–0.5 using the SRCUT model, describing an exponential cutoff in the population of the highest energy electrons accelerated by this SNR. In contrast, neither the SRESC model nor a simple power-law model yielded acceptable fits to the data. We find that the power-law fits obtained by Slane et al. (1999) to fit the spectrum of G347.3–0.5 over the energy range of 0.5–8 keV do not adequately fit the spectrum of this SNR at higher energies. We have also detected for the first time a thermal component to the X-ray emission from this SNR; this component appears to be more closely associated with central diffuse emission from the SNR than from the X-ray luminous rims. We estimate the ambient density surrounding the SNR to be \(0.05\ldots0.07\) cm\(^{-3}\); this value is consistent with the range of values obtained by Slane et al. (1999).

3. A weak emission feature is seen near 6.4 keV in our RXTE PCA spectra of G347.3–0.5 and our two background pointings which sample the GR. Because the strength and the line energy of this feature are approximately the same in all three pointings, we argue that the feature is associated with diffuse background emission from the GR rather than from G347.3–0.5 itself.

4. We have analyzed our RXTE PCA data to search for X-ray pulsations from the radio pulsar PSR J1713–3949, which lies near the center of G347.3–0.5 and may be associated with the SNR. We cannot confirm the presence of X-ray pulsations from this source, although our data are dominated by both cosmic-ray background and X-ray emission from the SNR and the GR, making the detection of pulsed signal from the pulsar difficult.

5. Based on our two-component (thermal and nonthermal) fits to the X-ray emission from the northwestern rim and the central diffuse emission from G347.3–0.5 and assuming a magnetic field strength of \(B = 10\ \mu\text{G}\), we estimate the maximum energy \(E_{\text{cutoff}}\) of accelerated cosmic-ray electrons to be 19–25 TeV, consistent with previous analyses. Fitting the broadband (radio to \(\gamma\)-ray) energy spectrum of G347.3–0.5 with a synchrotron-inverse-Compton scattering model yields values of \(8.8^{+1.1}_{-0.8}\) TeV for the maximum energy \(E_{\text{cutoff}}\) of the accelerated cosmic-ray electrons and a magnetic field of \(B = 150^{+250}_{-80}\) \(\mu\text{G}\). Our value for \(E_{\text{cutoff}}\) is sharply lower (but still consistent) with upper

### TABLE 6

| Property               | SN 1006 | Reference     | G266.2–1.2 | Reference     | G347.3–0.5 | Reference     |
|------------------------|---------|---------------|------------|---------------|------------|---------------|
| Distance (kpc)         | 2.2     | 1             | 1–2        | 2             | 6          | 3, 4          |
| Ambient density \(n\) (cm\(^{-3}\)) | \(\approx 0.1\) | 5 | 0.05\(^a\) | 2 | \(\approx 0.05\ldots0.07\) | 6 |
| Angular size (arcmin)  | 30      | 7             | 120        | 7             | 65 \(\times\) 55 | 7 |
| Dynamical age (yr)     | 997     | 1             | \(\approx 14000\) | 2 | \(\approx 8000\) | 4 |
| Flux density \(S_{20}\) (Jy) | 19    | 7             | 50(?)      | 7             | 4          | 4 |
| \(\alpha\)             | 0.6     | 7             | 0.3(?)     | 7             | \(\approx 0.55\) | 6 |
| \(B(\mu G)\)           | 9       | 8             | \ldots     | \ldots        | 150 \(\pm\) 250 | 6 |
| Progenitor type        | Ia      | 1             | II         | 2             | II         | 3, 4          |

\(^a\) Calculated from expressions provided by Slane et al. (2001) and assuming a mean distance of 1.5 kpc, a volume filling factor for a sphere of one-quarter and an explosion kinetic energy of \(10^{51}\) ergs.

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References.—(1) Winkler, Gupta, & Long 2003; (2) Slane et al. 2001; (3) Slane et al. 1999; (4) Ellison et al. 2001; (5) Allen et al. 2001; (6) This paper; (7) Green 2001; (8) Dyer et al. 2001.
limits derived by previous studies, while our value for $B$ is significantly higher than previously assumed. However, the ratio of volumes of TeV emission to X-ray emission derived by this fit ($V_{\text{TeV}}/V_{\text{X-ray}} \approx 1000$, with a lower limit of 360) is too large to be physically reasonable. While it appears that inverse Compton scattering cannot adequately fit the TeV emission from the northwest rim of G347.3–0.5, the other two high-energy processes associated with SNRs—neutral pion decay, as argued by Enomoto et al. (2002), and nonthermal bremsstrahlung—can be ruled out as well. This situation may change with the application of more sophisticated models which take into account curvature of the energy spectrum of electrons.

6. We have considered the gross properties of G347.3–0.5 and two other SNRs known to feature X-ray spectra dominated by nonthermal emission, SN 1006 and G266.2–1.2. We find that all three of these SNRs are dynamically young. X-ray–luminous but radio-weak SNRs expanding into regions of low ambient density. This suggests that low ambient density may play a key role in dictating that the X-ray spectrum from a SNR is dominated by nonthermal emission, although a more detailed study of the X-ray spectrum of other SNRs is required in order to test this hypothesis.

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