XMM-NEWTON, CHANDRA, AND CGPS OBSERVATIONS OF THE SUPERNOVA REMNANTS G85.4+0.7 AND G85.9−0.6

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ABSTRACT

We present an XMM-Newton detection of two low radio surface brightness supernova remnants (SNRs), G85.4+0.7 and G85.9−0.6, discovered with the Canadian Galactic Plane Survey (CGPS). High-resolution XMM-Newton images revealing the morphology of the diffuse emission, as well as discrete point sources, are presented and correlated with radio and Chandra images. The new data also permit a spectroscopic analysis of the diffuse emission regions, and a spectroscopic and timing analysis of the point sources. Distances have been determined from H i and CO data to be 3.5 ± 1.0 kpc for SNR G85.4+0.7 and 4.8 ± 1.6 kpc for SNR G85.9−0.6. The SNR G85.4+0.7 is found to have a temperature of ~12–13 MK and a 0.5–2.5 keV luminosity of ~10^{33} D_{8.5}^{-2} erg s^{-1} (where D_{8.5} is the distance in units of 3.5 kpc), with an electron density n_e of ~0.07–0.16 (f D_{8.5})^{-1/2} cm^{-3} (where f is the volume filling factor) and a shock age of ~9–49 (f D_{8.5})^{1/2} kyr. The SNR G85.9−0.6 is found to have a temperature of ~15–19 MK and a 0.5–2.5 keV luminosity of ~10^{34} D_{8.8}^{-2} erg s^{-1} (where D_{8.8} is the distance in units of 4.8 kpc), with an electron density n_e of ~0.04–0.10 (f D_{8.8})^{-1/2} cm^{-3} and a shock age of ~(12–42) (f D_{8.8})^{1/2} kyr. Based on the data presented here, none of the point sources appears to be the neutron star associated with either SNR.

Subject headings: ISM: individual (G85.4+0.7, G85.9−0.6) — stars: neutron — supernova remnants — X-rays: ISM

Online material: color figures

1. INTRODUCTION

In 2001, two new supernova remnants (SNRs) with low radio surface brightness, G85.4+0.7 and G85.9−0.6, were discovered in the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003) data and confirmed in X-rays with ROSAT data (Kothes et al. 2001). Both show distinct shells in the radio band with an extended region of X-ray emission in the center. The radio surface brightness of G85.4+0.7 at 1 GHz is S_{1 GHz} ≤ 1 × 10^{-22} W m^{-2} Hz^{-1} sr^{-1}, and the radio data also indicate that the SNR has a nonthermal shell with angular diameter ≈0.4′′ which is surrounded by a thermal shell with an angular diameter of ≈0.6′′ and is located within an H i bubble. The bubble also contains two B stars which may have been part of the same association as the SNR’s progenitor star. G85.9−0.6 has a radio surface brightness of S_{1 GHz} ≤ 2 × 10^{-22} W m^{-2} Hz^{-1} sr^{-1} and has no discernible H i features, indicating that it is expanding into a low-density medium, perhaps between the Local and Perseus spiral arms. The most likely event that would produce an SNR in such a region would be a Type Ia supernova.

X-ray observations are important to the study of SNRs, particularly those with low surface brightness, because they provide information about the morphology and emission processes of these objects, which are indicators of both the nature of the supernova explosion which formed them and the properties of the progenitor star. SNRs with low surface brightness are expected to be formed after the core collapse of a massive star in a Type Ib/c or Type II explosion, because the stellar wind would have blown away much of the interstellar medium (ISM) surrounding it, leaving a low ambient density into which the shock from the supernova expands. A Type Ia supernova can also result in a low surface brightness SNR if the surrounding ISM has a low density, such as it would if it were located between two spiral arms of the Galaxy. Thermal X-ray emission from an SNR arises as the blast wave of the explosion travels through and shocks the ISM, and as a reverse shock travels back into and shocks the ejecta. The X-ray spectrum of the SNR gives information about the temperature, density, and the luminosity of the shocked material, while imaging data provide information about the size and morphology of the region.

The low angular and spectral resolutions as well as the small number of counts in the ROSAT data did not allow spectroscopy nor detailed imaging to be done, so XMM-Newton observations, described in § 2, have been made in order to confirm the detection of the SNRs and to perform imaging, spectroscopic and timing studies. Detailed X-ray imaging, described in § 3, is used to map the diffuse emission and compare it to the location and size of the radio shells, and Chandra data have been used to search for compact objects not resolved by XMM-Newton. Spectral parameters obtained in § 4 lead to an estimate of such quantities as temperature, density, and luminosity of the SNRs. In § 5 the point sources are cataloged and an attempt at identification is made by matching their positions to objects in other catalogs. Timing analysis is performed to identify any pulsar candidates. The distances to the SNRs are derived from H i and CO data in § 6. The results are discussed in § 7.

Preliminary results were presented in Jackson et al. (2006) and Safi-Harb (2006).

2. OBSERVATIONS

2.1. XMM-Newton Observations

SNR G85.4+0.7 was observed with XMM-Newton on 2005 May 31 for 11.5 ks (Obs ID 0307130101, PI: S. Safi-Harb) and...
again on October 27 for 15.2 ks (Obs ID 0307130301, PI: S. Safi-Harb), because of proton flares in the first observation which made a large fraction of the data unusable. A 29 ks XMM-Newton observation was made of SNR G85.9–0.6 on 2005 November 24 (Obs ID 0307130201, PI: S. Safi-Harb).

The PN (Strüder et al. 2001) and MOS (Turner et al. 2001) data were reduced with the latest version of SAS (ver. 6.5.0), and events during proton flares were filtered out for producing images and spectra by using the SAS routines evselect to create rate files and tabgtigen to generate good time intervals (GTIs) for filtering the event files with the evselect routine. This rendered the first observation of G85.4+0.7 useful only for imaging, and slightly reduced the integration time, from 29 to 26 ks, for the G85.9–0.6 observation. The second observation of G85.4+0.7 shows no evidence for proton flaring, and the removal of proton flares did not significantly reduce the integration time. Images and spectra were created from the event files using evselect. The total effective exposure time for G85.4+0.7 was 14 ks for PN and 16 ks for the MOS, and for G85.9–0.6 it was 23 ks for PN and 26 ks for MOS.

To facilitate source detection, exposure maps were made using eexpmap and the images were combined using emosaic. The spectra were binned using a minimum of 25–50 counts per bin for the MOS instruments and 50 or 100 counts per bin for the PN for the point-source and diffuse spectra, respectively, using grppha. This latter grouping was necessary because the background subtraction added excessive noise to the spectra, particularly at high energies, where the spectra are background dominated. The background for both SNRs was calculated using various methods described in § 4.1.

2.2. Chandra Observations

A 14.5 ks observation of SNR G85.4+0.7 was made on 2003 January 26 (Obs ID 3898, PI: S. Safi-Harb) by the Advanced CCD Imaging Spectrometer (ACIS-S).7 SNR G85.9–0.6 was observed with ACIS-S for 20.2 ks on 2003 October 3 (Obs ID 3899, PI: S. Safi-Harb). Both observations were made at a focal plane temperature of −120°C.

The analysis of the Chandra data was done using Chandra Interactive Analysis of Observations (CIAO, ver. 3.3).8 For both Chandra observations, the data were corrected for charge transfer inefficiency (CTI) with tools provided by the ACIS team of Pennsylvania (Townsley et al. 2000). Events with ASCA grades (0, 2, 3, 4, 6) were retained, and periods of high background rates were removed. Data from hot pixels were eliminated. The effective exposure time for the observation of SNR G85.4+0.7 was 14.3 ks and of SNR G85.9–0.6 was 19.9 ks. The backgrounds for the point-source spectra were extracted from annuli surrounding the sources. The spectra were grouped with a minimum of 30 counts in each bin. Data from the S2 and S3 chips were used. Data from the other chips were not used because they do not overlap the XMM-Newton field of view.

3. IMAGING

The previous X-ray images from the ROSAT All-Sky Survey (RASS) did not resolve the SNRs and the point sources in the field, so the XMM-Newton PN and MOS data can be used to determine the nature of the sources. The results are described below.

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7 See the Chandra Proposers’ Observatory Guide (ver. 9) at http://cxc.harvard.edu/proposer/POG.
8 CIAO is available at http://cxc.harvard.edu/ciao.
sources 10, 11, 12, 13, 15, and 16 are situated well within the radio shell of the SNR, further investigation of these sources is not possible at this time.

3.2. G85.9–0.6

The XMM-Newton PN and MOS mosaic image of G85.9–0.6 with radio contours overlaid is shown in Figure 4. The image is smoothed in the same way as the G85.4+0.7 image, with a Gaussian filter with a 3 pixel radius. As with G85.4+0.7, the angular radius of approximately 5.8 arcmin and location of the X-ray emission shown in this figure matches that of Figure 6 of Kothes et al. (2001), and many features are resolved. The top and middle panels of Figure 5 show the 0.5–2.5 and 2.5–10.0 keV X-ray images. It is clear from the hard X-ray image that the SNR does not appear above 2.5 keV, and the X-ray spectrum is background dominated above 2.5 keV, as will be explored in § 4.3. The bottom panel of Figure 5 shows the same data as in the top panel with point-source emission subtracted, scaled to emphasize the diffuse emission. The contours in the bottom panel are smoothed to show the overall morphology of the remnant. The diffuse X-ray emitting region seems to be round in shape, indicating a centrally filled X-ray morphology. The circles in the top panel indicate spectral extraction regions described in §§ 4.3 and 7.4.

Spectra were extracted from eight point sources and the diffuse region, as indicated in the top panel of Figure 5. The analysis of the spectrum from the diffuse region is described in § 4.3, and § 5 describes the analysis of the point sources.

Figure 6 shows the Chandra image of SNR G85.9–0.6. The locations of the extraction circles for sources 1 and 8 in the XMM-Newton image are shown, in addition to the additional point
sources found on the Chandra image (labeled 9–27). The Chandra image does not show any point sources that have sufficient counts to do independent spectroscopic analysis, and only one of the sources identified from the XMM-Newton image (source 8) lies within the field of view of the Chandra image, with which a Chandra source has been identified.

4. SPECTROSCOPY

The spectra from the regions of diffuse emission were extracted from areas indicated in Figures 2 and 5 for both PN and MOS. The diffuse emission regions and point sources are indicated and labeled in the figures.

The spectra of the diffuse emission for both SNRs were fitted to various models: a simple bremsstrahlung model with Gaussian lines, VMEKAL, VNEI, and VPSHOCK, each modified by interstellar absorption, in this case the Wisconsin absorption model (\textit{wabs} in XSPEC; Morrison & McCammon 1983). VMEKAL is a collisional ionization equilibrium model based on the model calculations of Mewe et al. (1985) of the emission spectrum from hot diffuse gas with Fe calculations by Liedahl et al. (1990) with variable abundances. VPSHOCK is a nonequilibrium ionization (NEI) model with variable abundances which models a plane-parallel shock in a plasma with constant electron temperature \(T\) and a range of ionization timescales with an upper limit \(\tau = n_e t\), where \(n_e\) is the postshock electron density and \(t\) is the shock age (Borkowski et al. 2001). VNEI is a NEI model similar to VPSHOCK, except with a single ionization timescale.

4.1. Background Estimation

Spectra of diffuse faint regions require particular attention to be paid to the choice of background region. Instrumental emission lines can dominate the spectrum if the background region is poorly chosen, leading to errors in spectral fits and a discrepancy between the PN and MOS spectra. The intuitive background region would be a relatively source-free one at approximately the same Galactic latitude as the source to minimize contamination by the Galactic ridge. However, because the effect of instrumental emission lines is not uniform with position on the CCDs, particularly on the PN instrument (Lumb 2002), and exceeds the...
variation with Galactic latitude for these observations, the background regions were chosen as closely as possible to the point opposite the source region through the center of the image, taking care that there is no overlap between the source and background regions and omitting regions around point sources. The background regions for both SNRs are necessarily smaller than the source regions, but very little change in the spectral fits resulted from choosing various background regions in the same general area of the image.

An attempt has been made to estimate the MOS background spectra using the XMM-Newton Extended Source Analysis Software (XMM-ESAS; Snowden & Kuntz 2006). As yet, background estimation for the PN instrument is not included in this package. Data from filter wheel closed observations and from the unexposed corners of the MOS CCDs are used to generate background spectra. This serves as a test of the backgrounds generated from the observation itself, described above. To fit spectra using the XMM-ESAS backgrounds, it is necessary to include some additional spectral components, as recommended in Snowden & Kuntz (2006). Unabsorbed Gaussian lines of zero width at energies of 1.49 and 1.75 keV are fitted to the MOS spectra in addition to the model describing the emission from the SNR. The 1.75 keV line was also added to the fit to the MOS spectra using observation backgrounds because it was adequately subtracted, but the 1.49 keV line was added to the G85.9−0.6 MOS spectra using observation backgrounds. It was also necessary to include a low-energy broken power-law component to the G85.9−0.6 fit of the ESAS-subtracted spectrum, as instructed in the ESAS documentation, to correct for instrumental effects, because the statistics allowed residuals at low energies to be clearly seen in the ESAS-background-subtracted spectra. The broken power law was not added to the spectrum of G85.4+0.7 because the spectra were noisy and did not require an additional model component. Results of spectral fits using both background estimation methods for each SNR are given in Table 1. The parameters in columns (2) and (4) of Table 1 for each of the SNRs are from the simultaneous fit to the MOS spectra using the ESAS background subtraction method and the PN spectrum with the background spectrum extracted from the observation itself, and columns (3) and (5) contain the parameters from the simultaneous fit to the MOS and PN spectra from both of which has been subtracted the observation background.

As a third background subtraction method, we have attempted to use blank sky event files that are available for the PN and MOS instruments and generated to enable the production of background spectra for extended sources. These event files comprise a superposition of pointed observations from which sources have been removed. Background files produced from blank sky event files therefore simulate the detector response in an actual observation, including any instrumental emission lines. Events are first
selected from the original event files based on sky position using the SelectRADec script. The skyextract script (Read & Ponman 2003) is then used to cast the new event file onto the sky coordinates for the particular observation. The background spectra can be extracted from these files from the same region as for the source spectra. The BACKSCAL keyword is adjusted in the background file to scale it to the source file. Unfortunately, the resulting background-subtracted spectra are oversubtracted for the PN instrument and contain negative counts below 0.6 keV and above 1.5 keV. Thus, the blank sky background spectra cannot be used for this analysis. The oversubtraction possibly results from the fact that there are no observations within 30° of the SNRs G85.4+0.7 or G85.9—0.6 contained in the blank sky data sets, and therefore systematic errors arise from the different level of background emission. The background-subtracted PN spectra of G85.4+0.6 using a background from the observation itself and from the blank sky file are shown in Figure 7. The spectra from which the blank sky background was subtracted were not used, and thus the parameters do not appear in Table 1.

4.2. G85.4+0.7

The PN and MOS spectra between 0.5 and 2.5 keV are simultaneously fitted in order to determine the best parameters while reducing instrument-specific and systematic effects. The upper limit of 2.5 keV is used for the spectral fits because the spectra are background dominated above this energy as shown in Figure 7.

Fitting to the VMEKAL model results in a reduced $\chi^2$ value of 1.76 for the ESAS background or 1.63 for the observation background (this refers to the MOS spectra only; the background spectra extracted from the observation was used for every PN spectrum), and a $kT$ value of 0.65 ± 0.03 or 0.65 ± 0.01 keV (all errors are 2 $\sigma$) for the ESAS and observation background, respectively.

The spectra are best fitted with an absorbed VPSHOCK with $kT$ of 1.1$^{+0.5}_{-0.3}$ keV for the ESAS background or 1.0$^{+0.2}_{-0.1}$ keV for the observation background.

**TABLE 1**
Fits of G85.4+0.7 and G85.9—0.6 XMM-Newton PN and MOS Diffuse Region Spectra to an Absorbed VPSHOCK and Derived Quantities

| Parameter | XMM-ESAS Background | XMM-ESAS Background |
|-----------|---------------------|---------------------|
| $N_H$ (10$^{20}$ cm$^{-2}$) | 0.86$^{+0.04}_{-0.06}$ | 0.68$^{+0.03}_{-0.04}$ |
| $kT$ (keV) | 1.1$^{+0.03}_{-0.01}$ | 1.3$^{+0.07}_{-0.03}$ |
| $\tau$ (10$^{-3}$ cm$^{-1}$) | 6.4$^{+1.3}_{-2.8}$ | 6.8$^{+1.9}_{-1.6}$ |
| Norm$^{a}$ | 2.3$^{+0.4}_{-0.3}$ | 1.1$^{+0.1}_{-0.3}$ |
| $Q^b$ | 1.2 ± 0.5 | 1.5 ± 0.5 |
| Ne$^{c}$ | 0.4 ± 0.1 | 0.4 ± 0.1 |
| Mg$^{b}$ | 0.3 ± 0.1 | 0.1 ± 0.1 |
| Si$^{b}$ | 0.1 ± 0.1 | 0.1 ± 0.1 |
| S$^{b}$ | 0.4 ± 0.2 | 0.4 ± 0.2 |
| Fe$^{c}$ | 1.1 ± 0.3 | 2.6 ± 0.2 |
| $\chi^2/\nu$ | 1.41 (209) | 1.50 (460) |

**Note.**—Errors are 2 $\sigma$ uncertainties. Abundances of He, C, and N are frozen to solar. The Ni abundance is tied to the Fe abundance in the fits.$^a$Norm = (10$^{-14}$ erg/s/arcsec$^2$) / $n_e m_p$ cm$^{-3}$.$^b$Elemental abundances are relative to solar abundance.$^c$From the X-ray extraction radius in Figs. 2 and 5; $D_{1.5}$ and $D_{4.8}$ are distances in terms of 3.5 and 4.8 kpc, respectively.$^d$Flux in erg cm$^{-2}$ s$^{-1}$.$^e$The parameter $f$ is the volume filling factor.
the backgrounds extracted from the observation itself, and an ionization timescale of $6.4^{+0.5}_{-0.7} \times 10^{10}$ cm$^{-3}$ s for the ESAS background or $8.0^{+6.5}_{-3.4} \times 10^{10}$ cm$^{-3}$ s for the background extracted from the observation. The spectrum for the diffuse region is shown with the ESAS background in Figure 8 and with the observation background in Figure 9. The parameters for the simultaneous PN and MOS fits, with $2 \sigma$ uncertainties, are given in Table 1, along with derived quantities such as luminosity and age. The fitted parameters agree well within the uncertainty for the two background estimation methods. The abundances are for the most part consistent with solar, with exceptions given in Table 1. An analysis of the spectral fit parameters has shown G85.4+0.7 to have a 0.5–2.5 keV luminosity of $3.1^{+1.1}_{-0.7} \times 10^{33}$ or $2.0^{+1.6}_{-1.0} \times 10^{33}$ erg s$^{-1}$ for the ESAS or observation backgrounds, respectively, in both cases based on the estimated distance of $3.5 \pm 1.0$ kpc for G85.4+0.7, determined in §6. The normalizations of the instrumental lines in the MOS spectra from which the ESAS background has been subtracted are $(1.7 \pm 0.2) \times 10^{-5}$ and $5.5^{+0.9}_{-1.0} \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ for the lines at 1.49 and 1.75 keV, respectively. The normalization for the line at 1.75 keV for the observation background is $3.7^{+1.5}_{-1.0} \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$.

To verify the fits to elemental abundances, the VNEI model was used in place of VPShock. All elemental abundances were found to be consistent within error with solar or subsolar, except O and Fe. O was clearly enhanced above a solar value, giving strength to the VPShock result. The elemental abundances using the VMEKAL model were also qualitatively similar to the VPShock result.

### 4.3. G85.9–0.6

The approach used for fitting the diffuse spectra of G85.9–0.6 is similar to that used for G85.4+0.7. Again, the upper limit of 2.5 keV is used for the spectral fits because the spectra are background dominated above this energy. The PN diffuse spectrum was fitted simultaneously with the MOS spectra from which either the ESAS or observation background was subtracted.

Fitting to the VMEKAL model results in a reduced $\chi^2$ of 2.21 for the ESAS background and 2.48 for the observation background, and a $kT$ value of $0.70 \pm 0.01$ or $0.68 \pm 0.01$ keV.

The spectra of the diffuse emission from the remnants are best fitted with an absorbed VPShock model with $kT$ of $1.3^{+0.5}_{-0.3}$ keV for the ESAS background or $1.6^{+0.5}_{-0.3}$ keV for the background extracted from the observation, and ionization timescale of $6.8^{+1.9}_{-1.0} \times 10^{10}$ cm$^{-3}$ s for the ESAS background or $5.1^{+2.5}_{-1.5} \times 10^{10}$ cm$^{-3}$ s for the background extracted from the observation. The fitted parameters with $2 \sigma$ uncertainties are given in Table 1, and the diffuse spectrum with the ESAS background is shown in Figure 10 and with the observation background in Figure 11. The abundances are for the most part consistent with solar; the exceptions are shown in Table 1. The luminosity of G85.9–0.6 is $2.4^{+1.2}_{-1.0} \times 10^{34}$ erg s$^{-1}$ for the ESAS background or $2.7^{+1.2}_{-1.0} \times 10^{34}$ erg s$^{-1}$ for the observation background, in both cases based.
on the estimated distance of $4.8 \pm 1.6$ kpc for G85.9–0.6, determined in § 6. The normalizations for the 1.49 and 1.75 keV lines in the ESAS-subtracted MOS spectra are $(1.22 \pm 0.08) \times 10^{-4}$ and $3.7^{+0.5}_{-0.6} \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$, respectively. The broken power law which was added to the fit of the MOS ESAS-background-subtracted spectrum had $\Gamma_1 = 1.2^{+0.5}_{-0.3}$, $\Gamma_2 = 3.3^{+0.4}_{-0.3}$, $E_{\text{break}} = 0.91 \pm 0.05$ keV, and a normalization of $8.1^{+1.4}_{-1.0} \times 10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s at 1 keV. The normalization of the 1.75 keV line for the observation background is $(3.2 \pm 1.1) \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$.

When the VNEI model was used in place of VPSHOCK to check the elemental abundances, as was done with G85.4+0.7, all elemental abundances were found to be consistent within error with solar or subsolar, except O and Fe, both of which are clearly above solar abundance when the error bar is taken into account, in agreement with the VPSHOCK result. Using the VMEKAL model, the elemental abundances are again qualitatively similar to those obtained from the VPSHOCK model, except Mg is above solar.

5. POINT-SOURCE ANALYSIS

The previous ROSAT data of the SNR regions produced contours of the diffuse emission but did not resolve any point sources. The XMM-Newton and Chandra data considered at present allow for point sources to be resolved and located within the field of view. Nine clearly distinguishable point sources were found on the image of G85.4+0.7 (Fig. 2), of which six (sources 1, 2, 3, 4, 6, and 7) are in common with point sources in the Chandra observation, as shown in Figure 3. Twelve additional point sources are clearly resolved in the Chandra observation (labeled as sources 10–21 in Fig. 3), but they do not possess sufficient counts to allow for meaningful spectral analysis to be done. It should be noted that the B stars in Kothes et al. (2001) are outside the field of view of the X-ray observations. Eight point sources are seen on the XMM-Newton image of G85.9–0.6 (Fig. 5) of which only one source (source 8) is visible on the Chandra image, which is pointed toward the region encompassing sources 1 and 8 in Figure 5. Figure 6 also shows 19 additional point sources from the Chandra observation (labeled 9–27), but none of them possess sufficient counts for their spectral parameters to be sufficiently constrained. In the present work, the nine point sources detected with XMM-Newton in the field of G85.4+0.7 and eight in the field of G85.9–0.6 are analyzed using spectral and timing techniques, to locate any candidates for identification as neutron stars or pulsars which would have formed at the time of the supernova explosion.

5.1. Source Identification

To identify the X-ray point sources in the G85.4+0.7 and G85.9–0.6 fields, ewavelet, a wavelet detection algorithm which is part of the SAS version 6.5 package, is used. For each source, the output of the routine gives position on the image and in sky coordinates, source counts, and source extent, as well as errors in those quantities. Because the PN and MOS instruments have slightly different fields of view, only those sources found in the combined image
which are also found on the PN image are analyzed. The sources must also have an extent (size on the image) similar to the point-spread function (PSF) at that location on the image, and they must contain enough counts (>50) for the spectral and timing analysis.

A catalog of newly discovered X-ray point sources is given in Tables 2 and 3. The letters “XMMU” in the object designations indicate that they were discovered in XMM-Newton data, and a prefix of “CXO” indicates a discovery in Chandra data. The RASS catalog was checked to see if any of the sources appear there, and source 1 in the G85.9−0.6 image (Fig. 5) is well within the 24′′ 1σ error circle of the coordinates of the RASS object 1RXS J205911.3+444730, while source 1 in the G85.4+0.7 image (Fig. 2) lies marginally within the 24′′ 1σ error circle of the RASS object 1RXS J205058.7+452135. No other point sources in this study match any in the RASS catalog, indicating that these point sources are too faint to be included in the RASS catalog.

The sky coordinates of sources meeting the above criteria are searched within the extent, which is approximately the PSF size, in various catalogs, including the USNO-A2.0 catalog (Monet et al. 1998), the USNO-B1.0 catalog (Monet et al. 2003), the SKY2000 catalog (Myers et al. 2002), the catalog given in Guarinos (1992), and the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006), to determine whether the sources have already been identified in another wave band. Some of these catalogs give blue magnitude, and if this is converted into flux with the relation

\[ m_1 - m_2 = -2.5 \log \left( \frac{F_1}{F_2} \right) \]

and compared with the X-ray flux, this ratio is one factor that can be checked to favor identification as a neutron star. In the above equation, \( m_1 \) and \( m_2 \) are the blue magnitudes of the object and a standard star and \( F_1 \) and \( F_2 \) are their fluxes. Typical neutron stars have a flux ratio in optical/X-ray bands of \( \sim 10 \) (Lyne & Graham-Smith 1998), whereas X-ray emitting O- or B-type stars such as η Carinae (Corcoran et al. 2000) or τ Scorpii (Mewe et al. 2003) have a ratio of \( \sim 10^7 \), which enables an identification to be made of a neutron star candidate. The optical/X-ray flux ratios for the point sources, matched with each of the catalog objects within their extents, are shown in Tables 2 and 3. These values represent the optical/X-ray flux ratio should the catalog object match the X-ray source. If the optical catalog source and the X-ray point source are not the same object, the ratio is meaningless. However, an X-ray source without any optical counterparts within the PSF, such as source 6 or 7 from the G85.9−0.6 field, may be a good neutron star candidate. In other words, this test does not exclude X-ray point sources as neutron star candidates but rather indicates that a source emits in X-rays, is much fainter in the optical wave band, and is unlikely to be a stellar object. The optical/X-ray ratios for all point sources for which the ratio can be calculated (i.e., all sources except 6 and 7 in the G85.9−0.6 data, may be a good neutron star candidate. In other words, this test does not exclude X-ray point sources as neutron star candidates but rather indicates that a source emits in X-rays, is much fainter in the optical wave band, and is unlikely to be a stellar object. The optical/X-ray ratios for all point sources for which the ratio can be calculated (i.e., all sources except 6 and 7 in the G85.9−0.6 field) are \( >10^{11} \), which is much greater than the ratio expected for neutron stars, indicating that these objects are not neutron stars, assuming that the optical sources are the true counterparts. Other potentially interesting objects (e.g., neutron star
or AGN [active galactic nucleus] candidates) are Chandra sources 14, 16, 17, 18, 19, 21, 24, 25, and 27 in the G85.9–0.6 field, three of which have no counterpart at all (21, 24, and 27), and the rest of which have either only a 2MASS counterpart or a 2MASS counterpart that is a much better match for the position than the optical counterpart. These objects are shown in Figure 6 and listed in Table 3.

5.2. Spectral Analysis

In addition to the optical/X-ray flux comparison described in § 5.1, the X-ray spectra of the point sources can be examined to determine the likelihood that any of them are neutron stars. The X-ray spectrum of a rotation-powered pulsar is typically hard with a power-law photon index ($\gamma$) of approximately 0.5–2.1 (e.g., Gotthelf 2006), although there may be an additional blackbody component from the neutron star surface which could dominate the spectrum, depending on the age and the star’s magnetic field. Anomalous X-ray pulsars typically have photon indices between 2.4 and 4.6 (e.g., Woods & Thompson 2006). The background-subtracted spectra of the point sources, where the background region consists of an annulus surrounding each point source, are fitted to an absorbed power law, and the resulting fitted parameters are shown in Table 4. In addition, the 0.5–2.0 and 2.0–10.0 keV counts are given, which is particularly useful for estimating an X-ray hardness ratio when the fit to an absorbed power law yielded a large $\chi^2$ value, indicating an unsuitable model. Sources 1, 4, and 9 in the G85.4+0.7 field and sources 4, 6, and 7 in the field of G85.9–0.6 have been identified as neutron star candidates. Sources 1 and 9 of G85.4+0.7 both have photon indices of $\sim 2.5$, which does not rule them out as neutron star candidates, but they both have a high optical/X-ray flux ratio. Both source 4 of G85.4+0.7 and source 4 of G85.9–0.6 have a relatively soft X-ray spectrum compared with typical pulsars (and the $\chi^2$ value for the fit of source 4 on G85.9–0.6 indicates that the power-law model does not match the data well), and both have a high optical/X-ray flux ratio. However, it is not certain that the optical sources associated with these objects are the true counterparts. Neutron star candidates 6 and 7 in the G85.9–0.6 field have a photon index typical of neutron stars and no optical counterpart. However, source 6 has a column density ($N_H$) which is greater than that of the SNR itself, which indicates, along with its position relative to the SNR, that it is unlikely to be the associated neutron star. Source 7 has a $N_H$ value which is similar to that of the SNR, but its position indicates that it is probably not associated with the SNR. When considered separately, XMM-Newton and Chandra spectra of G85.4+0.7 point sources 1 and 3 yield spectral parameters which agree with each other well within the range of uncertainty. The Chandra spectra of sources 2, 4, 6, and 7 do not contain enough counts for independent spectral analysis, but the Chandra spectra for these sources are included in the analysis leading to entries in the appropriate rows of Table 4, and the spectral parameters of the combined XMM-Newton and Chandra spectra of
with a fit to an absorbed power law in Figure 12.

2 probability along with the number of bins is the number of bins in

undertake the uncertainty of those for the XMM-Newton spectra alone. As an example, the XMM-Newton PN and MOS and Chandra spectra of G85.4+0.7 source 1 is shown along with a fit to an absorbed power law in Figure 12.

5.3. Timing Analysis

A timing analysis is done on the PN data for the neutron star candidates identified above to search for pulsations. The timing resolution in PN full-window mode (68.7 ms) for both G85.4+0.7 and G85.9—0.6 allows for a search up to ~7 Hz, which would fail to identify fast rotation-powered pulsars, but would identify slowly rotating anomalous X-ray pulsars. The PN events file is first barycenter corrected. The photon arrival times for a region surrounding each source are used first in a fast Fourier transform (FFT) search to identify possible frequencies that should be investigated further. Around each frequency identified by the FFT search, Rayleigh (also known as $Z_\chi^2$; Leahy et al. 1983), $Z_\chi^2$ and $Z_\chi^2$ (Buccheri et al. 1983), and epoch-folding searches are done. The statistical significances of any identified frequencies are calculated using the $\chi^2$ probability along with the number of degrees of freedom, which is $2n$ for the $Z_\chi^2$ search and $n_{\text{bins}} - 1$ for the epoch-folding search, where $n_{\text{bins}}$ is the number of bins in the light curve. In this case the number of bins used is 12 and 20 for the two epoch-folding tests performed on the data, chosen because those numbers of bins produce a relatively detailed light curve while maintaining a reasonable number of counts per bin. With regard to the $Z_\chi^2$ test, the $Z_\chi^2$, $Z_\chi^2$, and $Z_\chi^2$ searches are performed and would identify typical pulsar X-ray light curves, which usually exhibit either a broad variation or two or three peaks per cycle.

The timing resolutions of the MOS instruments (which, in the data acquisition mode used for these observations, is 2.6 s) are not sufficient for meaningful timing analysis of this type to be done.

Of the six neutron star candidates found from the point-source spectra of the two observations, none were found to exhibit a periodic signal. However, a future dedicated timing search may uncover one of these sources as a pulsar.

5.4. Results of Point-Source Analysis

Based on a combination of the optical/X-ray ratios (assuming the optical sources are the counterparts of the X-ray sources), distances from the SNR centers, spectral parameters, and comparisons of $N_\text{H}$ value to that of the diffuse emission, none of the point...
and molecular hydrogen as a function of distance, by integrating the spectroscopic data down to the appropriate radial velocity. Neutral hydrogen data are from the Canadian Galactic Plane Survey (see Taylor et al. 2003 for further information), and the $^{12}$CO(1–0) molecular line data are from the Columbia CO survey of Dame et al. (1987).

Since atomic hydrogen is usually optically thick we could not simply integrate the H\textsc{i} emission, as emission does not represent all of the hydrogen actually present along a Galactic line of sight. To correct for this we have to determine the optical depth of the hydrogen along the line of sight. One way of doing this is by looking at the atomic hydrogen data. Neutral hydrogen data are from the Canadian Galactic Plane Survey (see Taylor et al. 2003 for further information), and the $^{12}$CO(1–0) molecular line data are from the Columbia CO survey of Dame et al. (1987). Sources is likely to be the neutron star candidate associated with the SNR. However, further observations of the Chandra objects may reveal one of them to be a neutron star or AGN.

**TABLE 3**

| Source No. | IAU Name | $\alpha_{2000.0}$ | $\delta_{2000.0}$ | Position Error (arcsec) | Counterpart | Offset (arcsec) | Optical/X-Ray Flux Ratio |
|------------|----------|------------------|------------------|------------------------|------------|-----------------|--------------------------|
| 1…………………| XMMU J205911.4+444729 | 20 59 11.398 | +44 47 29.27 | 11.3 | 1347–0402736\(^a\) | 5.5 | 1.1 × 10\(^{19}\) |
| 2…………………| XMMU J205950.5+445954 | 20 59 50.504 | +44 59 53.58 | 10.3 | HD 200102\(^b\) | 6.0 | 3.7 × 10\(^{15}\) |
| 3…………………| XMMU J205944.3+450741 | 20 59 44.261 | +45 07 40.75 | 11.7 | 1350–13269810 | 3.7 | 1.1 × 10\(^{14}\) |
| 4…………………| XMMU J205857.0+450348 | 20 58 56.993 | +45 03 48.25 | 11.0 | 1350–0403688\(^b\) | 3.7 | 1.0 × 10\(^{13}\) |
| 5…………………| J210003.3+450342 | 21 00 03.280 | +45 03 41.76 | 10.4 | 1350–13276811 | 4.3 | 2.5 × 10\(^{12}\) |
| 6…………………| J210023.1+454535 | 21 00 23.149 | +45 54 34.98 | 11.1 | 21002305+445634\(^d\) | 1.4 | ... |
| 7…………………| J210000.1+454631 | 21 00 00.057 | +45 56 30.94 | 9.3 | 2100003+445634\(^d\) | 4.9 | ... |
| 8…………………| J205917.0+445809 | 20 59 17.009 | +44 58 08.71 | 10.5 | 1349–0404180\(^b\) | 1.4 | 4.2 × 10\(^{12}\) |
| CXO J205917.3+445821 | 20 59 17.308 | +44 58 20.90 | 0.5 | ... | ... | ... |
| CXO J205917.5+445858 | 20 59 17.515 | +44 58 57.64 | 1.1 | 1275–14437760\(^e\) | 11.7 | 2.7 × 10\(^{14}\) |
| CXO J205917.7+445884 | 20 59 17.721 | +44 58 19.15 | 1.5 | 1275–14437760\(^e\) | 3.1 | 1.8 × 10\(^{13}\) |
| CXO J205923.5+445818 | 20 59 23.698 | +44 58 19.15 | 1.5 | 1275–14437760\(^e\) | 3.1 | 1.8 × 10\(^{13}\) |
| CXO J205929.2+445829 | 20 59 29.200 | +44 59 39.63 | 1.7 | ... | ... | ... |
| CXO J205930.8+445729 | 20 59 30.760 | +44 57 29.19 | 1.1 | 1349–0404462\(^b\) | 4.0 | 2.9 × 10\(^{13}\) |
| CXO J205932.7+445708 | 20 59 32.798 | +44 57 29.19 | 1.1 | 1349–0404462\(^b\) | 4.0 | 2.9 × 10\(^{13}\) |
| CXO J205929.1+445818 | 20 59 21.928 | +44 58 18.35 | 1.1 | ... | ... | ... |
| CXO J205920.0+445321 | 20 59 19.993 | +44 53 21.12 | 1.3 | ... | ... | ... |
| CXO J205912.6+445033 | 20 59 12.619 | +44 50 33.10 | 1.1 | ... | ... | ... |
| CXO J205904.1+445952 | 20 59 04.133 | +44 59 52.38 | 1.1 | ... | ... | ... |
| CXO J205957.7+450008 | 20 59 57.717 | +45 00 07.51 | 1.2 | ... | ... | ... |
| CXO J205851.5+450050 | 20 58 51.450 | +45 00 50.04 | 1.3 | ... | ... | ... |
| CXO J205848.7+450920 | 20 58 48.681 | +45 59 19.84 | 1.2 | ... | ... | ... |
| CXO J205841.1+452620 | 20 58 41.091 | +45 52 59.50 | 1.1 | ... | ... | ... |
| CXO J205837.4+455110 | 20 58 37.389 | +44 55 09.86 | 1.1 | ... | ... | ... |
| CXO J205834.6+445330 | 20 58 34.649 | +44 53 30.33 | 1.4 | ... | ... | ... |
| CXO J205814.7+444606 | 20 58 14.652 | +44 46 05.70 | 2.1 | ... | ... | ... |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Chandra positions are denoted by the prefix “CXO,” XMM-Newton positions by “XMMU.”

\(^a\) All designations are from the USNO-A2.0 catalog (Monet et al. 1998) unless otherwise noted.

\(^b\) USNO-B1.0 designation (Monet et al. 2003).

\(^c\) Designation in Guarinos (1992).

\(^d\) 2MASS designation (Skrutskie et al. 2006).

\(^e\) Refers to the XMM-Newton position.

\(^f\) Refers to the Chandra position.
Table 4
Parameters for Fits of XMM-Newton PN and MOS and Chandra Point-Source Spectra to an Absorbed Power Law

| Source No. | $N_H$ (10$^{22}$ cm$^{-2}$) | $\Gamma$ | PL Normalization | $\chi^2 (v)$ | 0.5–2.0 keV Counts | 2.0–10.0 keV Counts | Hardness Ratio | X-Ray S/N |
|------------|-----------------|--------|-----------------|-------------|-------------------|-------------------|---------------|----------|
| G85.4+0.7  |                 |        |                 |             |                   |                   |               |          |
| 1          | 0.50$^{+0.25}_{-0.18}$ | 2.47$^{+0.63}_{-0.47}$ | 4.75$^{+1.3}_{-1.0}$ | 1.20 (37) | 210 | 56 | 0.27 | 3.8 |
| 2          | 0.94$^{+0.27}_{-0.56}$ | 8.7$^{+1.3}_{-3.3}$ | 11.2$^{+1.9}_{-1.3}$ | 0.93 (14) | 122 | 0 | 0.00 | 7.2 |
| 3          | 0.70$^{+0.13}_{-0.09}$ | 4.9$^{+3.41}_{-2.73}$ | 4.58 (32) | 0.75 (12) | 92 | 0 | 0.00 | 6.2 |
| 4          | 0.33$^{+0.2}_{-0.1}$ | 3.8$^{+1.5}_{-1.5}$ | 2.83 (13) | 1.10 (13) | 150 | 50 | 0.33 | 4.8 |
| 5          | 1.1$^{+0.2}_{-1.0}$ | 9.5$^{+0.4}_{-0.4}$ | 13.2$^{+3.4}_{-3.4}$ | 2.32 (4) | 83 | 0 | 0.00 | 4.5 |
| 6          | 0.89$^{+0.18}_{-0.09}$ | 9.5$^{+0.5}_{-0.5}$ | 16.5$^{+0.3}_{-0.3}$ | 5.58 (24) | 139 | 0 | 0.00 | 4.8 |
| 7          | 0.8$^{+0.06}_{-0.09}$ | 8.7$^{+0.5}_{-0.5}$ | 17.3$^{+3.2}_{-3.2}$ | 0.73 (5) | 104 | 0 | 0.00 | 9.0 |
| 8          | 0.9$^{+0.19}_{-0.24}$ | 9.5$^{+0.5}_{-0.5}$ | 14.8 (9) | 1.17 (10) | 96 | 0 | 0.00 | 9.2 |
| 9          | 0.75$^{+0.31}_{-0.31}$ | 2.6$^{+1.0}_{-1.0}$ | 6.4$^{+0.6}_{-0.6}$ | 0.939 (17) | 86 | 43 | 0.33 | 3.2 |
| G85.9–0.6  |                 |        |                 |             |                   |                   |               |          |
| 1          | 1.04$^{+0.03}_{-0.06}$ | 9.5$^{+0.5}_{-0.3}$ | 117$^{+20}_{-20}$ | 7.73 (35) | 1230 | 20 | 0.016 | 35.4 |
| 2          | 1.4$^{+0.08}_{-0.08}$ | 8.5$^{+1.4}_{-1.4}$ | 53$^{+21}_{-21}$ | 3.87 (22) | 433 | 2 | 0.005 | 20.9 |
| 3          | 0.86$^{+0.05}_{-0.12}$ | 9.5$^{+0.5}_{-0.5}$ | 32$^{+15}_{-15}$ | 11.12 (18) | 417 | 0 | 0.00 | 20.4 |
| 4          | 0.53$^{+0.13}_{-0.21}$ | 3.9$^{+3.8}_{-3.8}$ | 4.4$^{+3.9}_{-3.9}$ | 2.13 (10) | 177 | 0 | 0.00 | 13.3 |
| 5          | 0.85$^{+0.79}_{-0.79}$ | 8.9$^{+4.3}_{-4.3}$ | 14.7$^{+14}_{-14}$ | 1.27 (6) | 117 | 18 | 0.15 | 11.6 |
| 6          | 1.37$^{+0.16}_{-0.16}$ | 1.56$^{+0.62}_{-0.62}$ | 9.9$^{+12.5}_{-12.5}$ | 1.07 (19) | 112 | 301 | 2.69 | 20.3 |
| 7          | 0.71$^{+0.06}_{-0.06}$ | 1.70$^{+0.44}_{-0.44}$ | 2.5$^{+1.9}_{-1.9}$ | 2.19 (10) | 26 | 90 | 3.46 | 10.8 |
| 8          | 0.46$^{+0.30}_{-0.21}$ | 5.3$^{+1.8}_{-1.8}$ | 5.0$^{+1.7}_{-1.7}$ | 1.71 (33) | 473 | 30 | 0.06 | 23.1 |
| 14         | ... | ... | ... | ... | 23 | 26 | ... | ... |

Note.—Chandra spectra are included in fit for sources 1, 2, 3, 4, 6, and 7 of G85.4+0.7 and source 8 of G85.9–0.6.

Power-law normalization in units of 10$^{-5}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

The hardness ratio is the ratio of hard counts to total (hard + soft) counts.

Figure 12.—XMM-Newton PN and MOS, and Chandra 0.5–5 keV spectra of G85.4+0.7 source 1, fitted to an absorbed power law. The fitted parameters are given in Table 4. The PN is shown by the solid black line, the MOS 1 and 2 are shown by the dashed blue and solid red lines, respectively, and the Chandra spectrum is shown by the dotted black line. The bottom panel displays the residuals in units of $\sigma$. 
column density integrated over the velocity interval $dv$ is then defined by $N_{\text{HI}}(v) = 1.8224 \times 10^{18} T_B(v) \tau(v) dv$, where $\tau$ is the optical depth, which can be determined from the absorption profile by $\tau(v) = -\ln \left( \frac{T_B(v) - T_{B\text{bg}}}{T_B(v) + 1} \right)$. Here $T_{B\text{bg}}$ is the brightness temperature of the absorbed background source, $T_B$ is the spin temperature of the absorbing cloud, which is defined by $T_B(v) = T_B(v)/(1 - e^{-\tau(v)})$. Equations for $N_{\text{HI}}(v)$, $\tau(v)$, and $T_B(v)$ can be found in, for example, Rohls & Wilson (2004).

To derive the complete foreground HI column, we have to add twice the molecular hydrogen column density $N_{\text{HI}}$. This is derived over the velocity interval $dv$ using its relation to the CO brightness temperature $T_B^{\text{CO}}$, determined by Dame et al. (2001): $N_{\text{HI}}(v) = 1.8 \times 10^{20} T_B^{\text{CO}}(v) dv$.

For the SNR G85.4+0.7 we used the absorption profiles of two background sources to determine the foreground atomic hydrogen column density. One source is located at the very center of the remnant (Fig. 13, source 1) at $l = 85.31^\circ$ and $b = +0.66^\circ$, and the other is just to the south (Fig. 13, source 2) at $l = 85.31^\circ$ and $b = +0.32^\circ$. For G85.9—0.6 we used the bright source at $l = 85.80^\circ$ and $b = -0.65^\circ$. To calculate the amount of foreground molecular hydrogen we averaged the Dame et al. (2001) CO data, which have a pixel size of 30$^\prime$ over the four pixels closest to the center of the X-ray emission. The final combined HI column density profiles are displayed in Figure 13.

If we now compare the absorbing HI column density, which we derived from the X-ray spectra (see Table 1), with the $N_{\text{HI}}$ velocity diagrams in Figure 13, we can get an estimate for the radial velocities of the SNRs. For the SNR G85.4+0.7 we derive a radial velocity of about $-9$ km s$^{-1}$ averaging over sources 1 and 2. This nicely confirms the radial velocity of $-12$ km s$^{-1}$, which was determined by Kothes et al. (2001) for the stellar wind bubble surrounding G85.4+0.7. For G85.9—0.6 no previous estimate of the radial velocity exists. The comparison of the absorbing HI column (Table 4) with the $N_{\text{HI}}$—velocity diagram in Figure 13 results in a radial velocity estimate of $-32 \pm 6$ km s$^{-1}$.

Previously, Kothes et al. (2001) found a distance to G85.4+0.7 of about $3.8 \pm 0.6$ kpc, based on the radial velocity of its host stellar wind bubble using a flat rotation model for the Galaxy with a galactocentric radius of 8.5 kpc for the Sun at a velocity of 220 km s$^{-1}$ around the Galactic center. A distance of $\approx 5$ kpc was predicted for G85.9—0.6. The radial velocities of G85.4+0.7 ($-12 \pm 3$ km s$^{-1}$) and G85.9—0.6 ($-32 \pm 6$ km s$^{-1}$) indicate they are beyond the solar circle ($R_0 = 7.6$ kpc; Eisenhauer et al. 2005), but from $T_B(l, v)$ diagrams in this direction they are not residents of the Perseus spiral arm (which shows as a large HI feature extended in longitude, very nearly centered on $-40$ km s$^{-1}$).

A new kinematic-based distance method has been developed by Foster & MacWilliams (2006). The approach is based on a model of the Galactic HI density distribution and velocity field, which is fitted to observations, rather than relying on a purely circular rotation model assigned to the object (as in standard kinematics). The model’s density component is that of a warped thick disk of HI, with axisymmetric features, and a two-arm density wave pattern in the disk. The velocity field component models a nonlinear response of the gas to the density wave (see Roberts 1969; Wielen 1979), producing shocks at the leading edge of major arms, and streaming motions within the disk, depending on the location of an object in the spiral phase pattern. This distance method has been shown to accurately reproduce spectrophotometric distances to HI regions throughout the second quadrant of the Galactic plane.

The best-fit synthetic HI profile (with velocity field as in Fig. 14) toward these objects shows that G85.4+0.7 is $3.5 \pm 1.0$ kpc distant. This distance indicates G85.4+0.7 is within the Local spiral arm, a feature in between the major Sagittarius and Perseus spiral arms of the Milky Way. While the velocity of G85.9—0.6 is less certain compared to G85.4+0.7 (determined by association with...
H; see Kothes et al. 2001), it should be noted that in the case of G85.4+0.7, comparison of the X-ray absorbing column to the total integrated hydrogen nuclei (in H and 12CO data) gives a very good velocity estimate. Hence, we can be reasonably sure that −32 km s⁻¹ is near the true velocity of G85.9−0.6 as well. This places it within the Perseus arm spiral shock, which is 4.8 ± 1.6 kpc in this direction (the arm’s potential minimum is 5.0 kpc). For any velocity in the range −40 km s⁻¹ ≤ ν_{LSR} ≤ −18 km s⁻¹, the distance range shown in the fitted velocity field (Fig. 14) is small, about 4.1–4.8 kpc.

Although SNRs stemming from Type II events are primarily found within the arms (as massive progenitors are born mainly in the arm’s shock; Wielen 1979), the location of G85.9−0.6 within the shock does not necessarily vitiate its identification as a Type Ia. For example, Tycho’s SNR is known to be Type Ia, but its velocity and distance clearly associate it with the Perseus spiral arm. It is possible that the binary precursor of G85.9−0.6 migrated into the arm along its Galactic orbit before exploding as a Type Ia event.

7. DISCUSSION

7.1. Determination of Shock Age and Mass of Emitting Gas

To estimate τ, the shock age, for the SNRs, the relation $τ = τ/n_e$ is used, where τ is the upper limit of the ionization timescale from the VPSHOCK model. The electron density $n_e$ is determined from the distance in centimeters $D_{\text{cm}}$, angular size in radians $α$, given by the diameter of the extraction region, and the relation $n_{\text{HI}} = n_e/1.2$, where $n_{\text{HI}}$ is the volume density of hydrogen within. Given that

$$n_e = \frac{2.88 \times 10^{-5} \text{(Norm)}}{f \alpha^3 D_{\text{cm}}^2}$$

From these calculations, it is determined that for G85.4+0.7, $n_e ≈ (0.11 ± 0.03)(fD_{\text{cm}})^{-1/2}$ for the ESAS background (for the MOS instrument) or $0.11 ± 0.05(fD_{\text{cm}})^{-1/2}$ for the observation background, and $τ = 18^{+27}_{-3} (fD_{\text{cm}})^{1/2}$ kyr for the ESAS background or $23^{+20}_{-14} (fD_{\text{cm}})^{1/2}$ kyr for the observation background. For G85.9−0.6, $n_e ≈ 0.07 ± 0.03(fD_{\text{cm}})^{-1/2}$ for the ESAS background or $(0.07 ± 0.03)(fD_{\text{cm}})^{1/2}$ kyr for the observation background, and $τ = 30^{+12}_{-13}(fD_{\text{cm}})^{1/2}$ kyr for the ESAS background or $22^{+11}_{-10}(fD_{\text{cm}})^{1/2}$ kyr for the observation background. These are larger than the age estimates from the radio data.

The mass of the emitting gas is calculated based on spherical emission regions with the size given by the extraction radius (given in Table 1), composed of 92% hydrogen and 8% helium, and the relation $m = n_e/1.2$ is used as for the above calculation of $τ$. The mass of the emitting gas in G85.4+0.7 is $(2.8 ± 1.5)D_{\text{cm}}^2 M_\odot$ for the ESAS background and $(2.8 ± 1.5)D_{\text{cm}}^2 M_\odot$ for the observation background, and that for G85.9−0.6 is $2.7^{+1.8}_{-1.6} D_{\text{cm}}^2 M_\odot$ for the ESAS background and $(2.7 ± 1.8)D_{\text{cm}}^2 M_\odot$ for the observation background.

7.2. Background Subtraction

The background subtraction was problematic, particularly for the spectrum of G85.4+0.7, which is fainter and required a different model to be fitted to it depending on which background region on the observation was used, leading to a very careful selection of the background extraction region, the process of which is described in § 4.1. Instrumental lines, which are fortunately different for PN and MOS, nevertheless increased the value of $\chi^2$ for the combined fits, even when the background was chosen very carefully, and needed to be explicitly fitted when the ESAS background was used, as described in § 4.1. In addition, the soft spectra of the SNRs exhibit large amounts of noise in the high-energy end of the spectra, allowing fits to be made only up to 2.5 keV. Future longer observations of these SNRs will help resolve these difficulties, allow for better fits to the abundances, eliminate ambiguities in the spectral results, and perhaps allow for conclusive identifications of neutron star and pulsar candidates in addition to other point sources.

7.3. G85.4+0.7

A comparison between the morphologies of the X-ray diffuse emission and the radio emission of G85.4+0.7 can be seen in Figure 15 in which the X-ray point sources have been removed and the X-ray image has been smoothed to 1' to match the radio contours. The diffuse X-ray emission exhibits some structure, and it lies in the approximate center of the radio shell. A spectrum was extracted from the central blob, the position and size of which is shown in the top panel of Figure 2, and it could not be adequately fitted with a nonthermal power-law model, indicating that a pulsar wind nebula origin for the emission can be ruled out.

The fact that the SNR does not exhibit any limb brightening and the X-ray emission is mostly concentrated in the center, as projected in the plane of the sky and three-dimensionally, can be interpreted as evidence that the X-ray emission is produced by the ejecta. The fact that there appears to be no emission from the
swpt-up material can be explained if the remnant is evolutionarily young.

With the ejecta interpretation, if it is assumed that the free electrons are evenly distributed in the extraction area, the resulting ages are 18 and 23 kyr for the two backgrounds. In Figure 15 it can be seen that the outer radio shell has an approximately constant radius, whereas the inner shell has a smaller radius in the vertical center, which expands as the latitude changes, and this indicates that the SNR is moving either toward us or away from us. The two shells appear to meet near the bottom of the image, so the radius of the SNR can be approximated as that of the outer shell, which is ~0.3" on the image. The average velocity of the expanding SNR is then 910 or 730 km s\(^{-1}\) for the two ages. However, the morphology of the X-ray emission is not very smooth, indicating that the filling factor \(f\ll 1\). Assuming \(f = 0.2\), the electron density \(n_e\) would be 0.25 cm\(^{-3}\) for either the ESAS or the observation background, and the ejecta masses would be 1.3 \(M_\odot\) for each background. The shock age would then be 8000 or 10,300 yr, and the average expansion velocity would be 2150 or 1640 km s\(^{-1}\). For a 10\(^{51}\) erg supernova explosion, the ejecta mass would be 22 or 37 \(M_\odot\), or 2.2 or 3.7 \(M_\odot\) for a 10\(^{50}\) erg explosion, indicating that the lower energy explosion would result in an ejecta mass consistent with a young freely expanding SNR.

The radio continuum emission indicates that there is some swept-up material. Assuming that the density inside the stellar wind bubble was ~0.01 cm\(^{-3}\) before the explosion, the SNR would have swept up ~6.5 \(M_\odot\) of material, which is on the order of the ejecta mass, and means that the SNR is in the transition between free expansion and Sedov expansion.

The slightly above solar abundance of O in the diffuse spectra reinforces the hypothesis that the supernova most likely resulted from a core collapse, although the large error bars weaken the argument. The abundances of all elements other than O and Fe are below solar, but they would be enhanced if the X-rays were from the ejecta. However, it is possible that the spectral parameters for the abundances are affected by the poor quality of the spectra and by the uncertainties associated with the background subtraction.

Since the most likely origin of G85.4+0.7 was a core collapse supernova (see § 6), it is possible that a neutron star or pulsar which is associated with this SNR can be found. Given its powerlaw X-ray spectrum, proximity to the center of the remnant, and similar \(N_H\) value to the diffuse emission, source 1 in Figure 2 is possibly the associated neutron star, but sources 4 and 9 are within the radio shell and are also candidates, given their spectral parameters. However, the low fit quality of source 4 (\(\chi^2 \sim 2\)) indicates that it is not likely to be a neutron star, and source 9 is situated far from the center of the diffuse emission and so is less likely to be the associated neutron star. Chandra sources 10, 11, 12, 13, 15, and 16 in Figure 3 can also be considered as neutron star candidates (provided the optical counterparts listed in Table 2 are not the true counterparts).

7.4. G85.9-0.6

Figure 16 shows X-ray and radio images of G85.9-0.6, produced in a similar way to Figure 15. The diffuse X-ray emission appears to contain less structure than G85.4+0.7, and, as for G85.4+0.7, a spectrum extracted from the central blob, the position and size of which are shown in the top panel of Figure 5, indicates that a pulsar wind nebula origin for the emission can be ruled out.

Because Figure 15 shows no limb brightening and the emission is mostly from the central blob, a similar argument to that used for G85.4+0.7 can be employed here to suggest an ejecta interpretation for the X-ray emission. Assuming that the free electrons are evenly distributed in the extraction area, the resulting age is 30 or 22 kyr for the two backgrounds. Using the average distance between the center of the X-ray emission and the shell, ~0.2", the radius of the shell is 15.3 pc. The average expansion velocity would then be 500 or 680 km s\(^{-1}\). The emission is concentrated in the inner 6', which indicates an electron density of...
0.20 cm\(^{-3}\) and an ejecta mass of 1.0 \(M_{\odot}\), which agrees with the predicted mass for a Type Ia explosion, 1.4 \(M_{\odot}\). This would result in an age of 10,600 or 7800 yr and average expansion velocity of 1350 or 1850 km s\(^{-1}\).

For a Type Ia supernova, the explosion energy is \(\sim 10^{51}\) erg and the ejecta mass is 1.4 \(M_{\odot}\). Unlike for G85.4+0.7, the density in the interarm region is closer to 0.1 cm\(^{-3}\), resulting in a swept-up mass of nearly 50 \(M_{\odot}\). This indicates that the SNR is in the S\'edov expansion phase, which is described by \(R = 14(E_0/n_0)^{0.6}t^{2/5}\), where \(R\) is the radius in pc, \(E_0\) is the explosion energy in units of \(10^{51}\) erg, \(n_0\) is the ambient density in cm\(^{-3}\), and \(t\) is the age in units of \(10^4\) yr. For an explosion energy of \(10^{51}\) erg, a radius of 15.3 pc, and an age of 10,600 or 7800 yr, the resulting ambient density is 0.84 or 0.55 cm\(^{-3}\) which are consistent with the density of the interarm region, but the swept-up mass would be 360 or 240 \(M_{\odot}\), from which it should be possible to measure thermal X-ray emission, from the part of the shell that is included in the X-ray pointing. The current expansion velocity would be \(dR/dt = 0.4(R/t)\), which is 570 or 760 km s\(^{-1}\).

The interpretation of G85.9—0.6 as having been produced by a Type Ia supernova is reinforced by the Fe abundance, which is well above solar. As with G85.4+0.7, the ejecta interpretation is called into question by the remaining abundances, which should be above solar, but are instead below solar. This could again be a result of poor-quality spectra.

Given that the radio results described in Kothes et al. (2001), as well as the distance presented here, indicated that G85.9—0.6 was most likely produced by a Type Ia supernova, we did not expect to find a neutron star associated with this SNR. The above-solar Fe abundance for this SNR is consistent with a Type Ia explosion. An identification of sources 6 and 7 in Figure 5 has not yet been made. They are bright X-ray emitting objects with no known optical or radio counterpart, making them good neutron star or radio-quiet AGN candidates, although if one of them were a neutron star, it would be unlikely that it is associated with the G85.9—0.6 SNR because they are both situated far outside the radio shell of the remnant. Furthermore, the value of \(N_H\) for source 6 does not match that of the SNR itself, and the fit quality of source 7 (\(\chi^2 \approx 2\)) indicates that an absorbed power law is not a good fit. Their identification with possible 2MASS counterparts (see Table 3) makes them more likely radio-quiet AGNs than neutron stars, provided the 2MASS objects are the true counterparts. A future detailed deep X-ray or multiwavelength study of these objects should be undertaken to identify and further study them, even though they are probably not associated with the G85.9—0.6 SNR. Source 4 is on the edge of the radio shell of the SNR, but its identification as a neutron star is questionable because of its photon index and hardness ratio, as well as the fact that a neutron star is not expected to be associated with this remnant.

### 7.5. Mixed Morphology Interpretation

The centrally filled morphology of both SNRs and the thermal nature of their X-ray emission confined within the radio shells suggest that they belong to the class of mixed-morphology SNRs (also known as thermal composites; Rho & Petre 1997). The origin of the thermal X-ray emission interior to the radio shells in these SNRs has been attributed to several mechanisms, which include: (1) cloudlet evaporation in the SNR interior (White & Long 1991), (2) thermal conduction smoothing out the temperature gradient across the SNR and enhancing the central density (Cox et al. 1999), (3) a radiatively cooled rim with a hot interior (e.g., Harrus et al. 1997), and (4) possible interaction with a nearby cloud (e.g., Safi-Harb et al. 2005). While modeling these SNRs in light of the above-mentioned models is beyond the scope of this paper and has to await better quality data, we can rule out the cloudlet evaporation model based on the low ambient densities inferred from our spectral fits (see § 7.1 and Table 1). Except for Fe and possibly O, the abundances inferred from our spectral fits are consistent with or below solar values, as observed in most mixed-morphology SNRs. However, enhanced metal abundances have been observed in younger SNRs, such as 3C 397, estimated to be \(\sim 5.3\) kyr old and proposed to be evolving into the mixed-morphology phase (Safi-Harb et al. 2005). The ages inferred for G85.4+0.7 (8–10 kyr; see Table 1 and § 7.3) and G85.9—0.6 (8–11 kyr; see Table 1 and § 7.4) suggest a later evolutionary phase where only shock-heated ejecta from Fe (for G85.9—0.6) and possibly O are still observed.

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