Chapter 7

The New Pulsar-Supernova Remnant System PSR J1119−6127 and SNR G292.2−0.54

7.1 Introduction

PSR J1119−6127 was discovered by Camilo et al. (2000) in an on-going survey of the Galactic plane at the Parkes 64−m radio telescope in Parkes, Australia (Lyne et al. 2000). While its period of 0.4 s is relatively long compared to that of the young Crab-like pulsars, its period derivative of $4 \times 10^{-12}$ is the largest of any known radio pulsar. The characteristic age, calculated from these spin parameters, is $\tau_c \equiv P/2 \dot{P} = 1600$ yr (see Equation 6.9), third youngest among any pulsars. In addition to its extreme youth, PSR J1119−6127 also has an extremely large inferred surface magnetic field of $B \equiv 3.2 \times 10^{19} (P \dot{P})^{1/2}$ G = $4 \times 10^{13}$ G (see Equation 6.5), ranking second among all known rotation-powered pulsars.

PSR J1119−6127 is also noteworthy as it is one of only a few pulsars that has an accurately measured second period derivative $\ddot{P}$, which allows determination of the braking index $n \equiv \nu \ddot{\nu}/\dot{\nu}^2 = 2 - (P \ddot{P}/\dot{P}^2)$ (see Equation 6.7). Even more important is that the value of $n = 2.91(5)$ makes PSR J1119−6127 the neutron star with a braking
index closest to three, the value expected if a pulsar spins down via magnetic dipole braking. In many ways, PSR J1119−6127 is similar to PSR B1509−58, another long-period young pulsar for which \( n \) is measured. Table 7-1 presents the spin parameters and derived quantities for both of these pulsars. In the same way that the discovery of PSR B0540−69, taken with the Crab pulsar, established the existence of a class of fast, young pulsars with large spin-down luminosities, PSR J1119−6127 suggests that PSR B1509−58 is also the archetypical member of a class of young, high-magnetic field pulsars with periods of hundreds of milliseconds.

After the pulsar’s discovery, relevant publicly accessible data archives were searched for observations with PSR J1119−6127 in their field of view. A Galactic survey performed with the Molonglo Observatory Synthesis Telescope (MOST) at 843 MHz revealed a faint ring-like shell, \( \sim 14' \) in extent and approximately centered on the position of the pulsar. A brief ROSAT PSPC observation shows X-ray emission coincident with a portion of the radio shell. Recently, radio interferometric observations of PSR J1119−6127 and its vicinity have been made with the Australia Telescope Compact Array (ATCA) at several frequencies (Crawford 2000; Crawford et al. 2000). These data not only confirm the existence of the shell-like emission, but have a spectral index consistent with that of all other known SNRs. These multi-wavelength data clearly prove the existence of a SNR, and taken together with the prospect of detecting emission from the pulsar, warrant a deep X-ray observation. Below, we present detailed analysis of both the pointed ASCA and serendipitous ROSAT observations.

### 7.2 Observations

ASCA (Tanaka, Inoue, & Holt 1994) observed PSR J1119−6127 during a 36 hour period spanning 1999 August 14 − 15 as part of the AO−7 Guest Observer program (sequence number 57040000). The mean MJD of this observation (51404.4) is just six days after a glitch reported by Camilo et al. (2000). See § 7.3.2 for more details. To achieve the time resolution necessary for pulsation searches, the GIS (Gas Imaging
Table 7-1. Astrometric and spin parameters for PSRs J1119–6127 and B1509–58.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PSR J1119–6127</th>
<th>PSR B1509–58</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right ascension (J2000)</td>
<td>11 19 14.30</td>
<td>16 15 55.62</td>
</tr>
<tr>
<td>Declination (J2000)</td>
<td>−61 27 48.5</td>
<td>−59 08 09.0</td>
</tr>
<tr>
<td>Period, $P$ (ms)</td>
<td>407.64</td>
<td>150.66</td>
</tr>
<tr>
<td>Period derivative, $\dot{P}$</td>
<td>$4.023 \times 10^{-12}$</td>
<td>$1.537 \times 10^{-12}$</td>
</tr>
<tr>
<td>Second period derivative, $\ddot{P}$</td>
<td>$3.59 \times 10^{-23}$</td>
<td>$1.31 \times 10^{-23}$</td>
</tr>
<tr>
<td>Epoch of period (MJD)</td>
<td>51398</td>
<td>48355.00</td>
</tr>
<tr>
<td>Braking index, $n$</td>
<td>2.91 ± 0.01</td>
<td>2.837 ± 0.001</td>
</tr>
<tr>
<td>Dispersion measure, DM (pc cm$^{-3}$)</td>
<td>707</td>
<td>253</td>
</tr>
<tr>
<td>Characteristic age, $\tau_c$ (yr)</td>
<td>1606</td>
<td>1554</td>
</tr>
<tr>
<td>Spin-down luminosity, $\dot{E}$ (ergs s$^{-1}$)</td>
<td>$2.34 \times 10^{36}$</td>
<td>$1.77 \times 10^{37}$</td>
</tr>
<tr>
<td>Magnetic field, $B$ (G)</td>
<td>$4.1 \times 10^{13}$</td>
<td>$1.5 \times 10^{13}$</td>
</tr>
</tbody>
</table>

Note. — Information for PSR B1509–58 is taken from Kaspi et al. (1994), that for PSR J1119–6127 is taken from Camilo et al. (2000).
Spectrometer) was operated in a slightly non-standard mode. Time resolution of 0.488 ms or 3.91 ms (depending on the telemetry rate) was achieved by sacrificing information about the time characteristics (or “Risetime”) of detected events, one way to differentiate between background and celestial X-ray photons. (See §7.3.1 for a discussion on the ramifications of this operation mode.)

The SIS (Solid-state Imaging Spectrometer) can be operated in one-, two-, or four-chip mode, with a corresponding field of view (FOV) of 11′ × 11′, 11′ × 22′, or 22′ × 22′ and time resolution of 4 s, 8 s or 16 s. Given the extent of the radio shell, four-chip mode with its large FOV would have been the ideal operation mode. However, after more than six years in the harsh radiation environment of a low-Earth orbit, the SIS detectors have degraded significantly. Longer integration times result in the accumulation of large amounts of dark current, greatly reducing spectral resolution.

As a compromise between achieving a FOV wide enough to encompass a large fraction of the shell and obtaining potentially useful spectroscopic information from the CCDs, the SIS was operated in two-chip mode. As for PSRs B1046−58 and B1610−50 (see Chapter 6), the data were analyzed using the standard (i.e. REV 2) screening criteria suggested in the *The ASCA Data Reduction Guide*. The resulting effective exposure times for each type of detector are 37 ks (GIS) and 34 ks (SIS).

*ROSAT* (Trümper 1983) serendipitously observed the field around PSR J1119−6127 with the Position Sensitive Proportional Counter (PSPC) on 1996 August 14 during an 11 ks pointed observation of NGC 3603 (sequence number RP900526N00). After retrieving the data from the NASA-maintained HEASARC archive, we used the already-processed and filtered data for our subsequent analysis. PSR J1119−6127 is located 31′ away from the optical axis, and due to vignetting and obscuration from the mirror support structure, the effective exposure time for a 15′ diameter circle centered on the pulsar is between 6.4 − 8.9 ks.

\[\text{http://legacy.gsfc.nasa.gov/docs/asca/abc/abc.html.}\]
7.3 Data Reduction

7.3.1 Image Analysis

ASCA

Flat-fielded images are generated by aligning and co-adding exposure-corrected images from pairs of instruments. First, exposure maps were generated with the FTOOL ascaexpo, software that incorporates the satellite aspect solution and instrument information (i.e. GIS grid structure and SIS chip alignment and hot-pixel lists) to calculate the exposure time for each sky image pixel. The possibility of detecting extended emission coincident with the radio shell makes folding detector effects accurately into this procedure crucial. This is particularly relevant for the GIS, as removing artifacts from the window support grid and the X-ray background are the only way to detect low surface brightness features. The recently released FTOOL mkgisbgd\(^2\) can be used for generating a reliable GIS map.

Unfortunately, this software relies upon input data that were screened using Rise-time information, making it inappropriate for our observation. To remedy this data-type mismatch, we have undertaken re-analysis of the 2.1 Msec of archival data that mkgisbgd uses. The data sets consists of all high latitude GIS observations taken between 1993 June and 1995 December. Using the masks generated by Ishisaki (1997), all sources brighter than \(2 \times 10^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\) are subtracted from the field of view. Then, the data were analyzed using the standard REV 2 criteria, omitting the step dependent on the Risetime parameter. Finally, these appropriately-screened data were used with mkgisbgd to generate detector maps valid for our observations. Refer to the HEASARC web site\(^2\) for additional details.

Next, the SIS data are rebinned by a factor of 4 (6.73 pixel\(^{-1}\)) and data from both instruments are smoothed with a kernel representing the point spread function (PSF) of the X-ray telescope (XRT) and detector combination. We approximate this

\(^2\)http://heasarc.gsfc.nasa.gov/docs/asca/mkgisbgd/mkgisbgd.html
function with a Gaussian of $\sigma = 30''$ for the SIS and $\sigma = 45''$ for the GIS. Finally, we correct the astrometric position of the smoothed images for known errors in the pointing solution using the FTOOL offsetcoord$^3$.

Figure 7-1 shows the resultant images for both the GIS (left) and SIS (right). X-ray events were filtered by energy to make images in three different bands: broad (0.8−10.0 keV [top]), soft (0.8−3.0 keV [middle]), and hard (3.0−10.0 keV [bottom]). The color scale for each plot indicates the count rate in units of counts s$^{-1}$ arcmin$^{-2}$. In each plot, the radio position of PSR J1119−6127 is marked by a cross. Each plot also displays the contours from the recent 20 cm ATCA radio observations (Crawford 2000; Crawford et al. 2000) of the field around the pulsar. Contour levels span from 10% to 90% of maximum (7.1 mJy beam$^{-1}$) in increments of 10%. Both instruments show significant emission from a nearly-circular region that roughly matches the radio SNR morphology. On the basis of this and other evidence presented below, we classify this extended emission as the previously unidentified X-ray bright supernova remnant G292.2−0.54. The right (western) side of the SNR exhibits marked enhancements in X-ray flux at energies below 3 keV, while at higher energies the emission is relatively uniform throughout the entire SNR.

In addition to the X-ray bright SNR, the GIS shows evidence for a hard point-like source in the middle of G292.2−0.54. To estimate the significance of this detection, we compare the number of photons detected in a small aperture centered on the source with those from a concentric annulus, used to estimate the local background. Since the broad wings of the GIS+XRT PSF has extent of $\sim 4'$, ideally the source aperture would be of similar size, and the background annulus would have large inner and outer radii (e.g., 5' and 9'). However, in our case the source is embedded in non-uniform diffuse emission, greatly complicating the analysis. As a compromise, we use a source aperture of radius 2'5 and a background annulus with radii 3'25 and 5'0, realizing that the derived detection significance $\sigma$ will only provide a lower

$^3$For a full description of this procedure and the specific parameters used, refer to http://heasarc.gsfc.nasa.gov/docs/asca/coord/updatecoord.html.
Figure 7-1  ASCA images of the field around PSR J1119–6127. Images are from the GIS (left) and from the SIS (right). Images for three separate energy bands are shown in each row: broad-band (0.8 – 10 keV [top]), soft-band (0.8 – 3.0 keV [middle]), and hard-band (3.0 – 10 keV [bottom]). In each image, the location of PSR J1119–6127 is marked by a cross. The contours are from 20 cm ATCA observations and range from 10% to 90% of the maximum value (0.7 mJy beam$^{-1}$) in increments of 10%. The color bars in each plot indicate counts sec$^{-1}$ arcmin$^{-2}$. The X-ray emission, classified here as the previously unknown SNR G292.2–0.54, roughly traces the radio morphology in the broad- and hard-bands, although significant enhancement is seen on the western (right) side of the SNR below 3 keV. A hard point-like source is clearly evident in the GIS image.
limit to the source strength. Using the signal-to-noise ratio defined in Appendix D, we calculate a significance of $\sigma \gtrsim 4.0$ for the 158 background-subtracted photons detected with energies between $3 - 10$ keV. To explore the possibility that the source is an instrumental artifact, we examined individual images from GIS–2 and GIS–3. Emission is present in both detectors at the above position, verifying the celestial nature of the source.

No point-like source is seen in the hard-band SIS image, although there is enhanced emission at the source position derived from the GIS data. Using aperture and annulus radii (2′0, 3′25, and 4′5, respectively) appropriate for the smaller SIS+XRT PSF, we calculate a significance of $\sigma \gtrsim 3.5$ for the 59 background-subtracted photons detected between $3 - 10$ keV. The lack of a strong point-like feature in the SIS when one is present in the GIS is not uncommon and results from instrumental effects, including the larger effective area of the GIS (Gotthelf, private communication).

Fitting a two-dimensional Gaussian to the GIS source distribution, we measure a position of $\alpha$ (J2000) = 11h 19m 4·5, $\delta$ (J2000) = $-61^\circ$ 28′ 32″ with a formal positional uncertainty of $\sim 10''$. We classify this source as AX J1119.1−6128.5. The absolute pointing uncertainty of ASCA, after making the known corrections mentioned above, has an error radius of 30″ at the 90% confidence level (Gotthelf et al. 2000). The source is located 82″ away from PSR J1119−6127, more than twice as large as the combined positional errors. However, we note that in at least one documented case, the ASCA-measured position of a source was 80″ from the well-established position (Gotthelf et al. 2000). Thus, while the offset of the GIS source from the pulsar is larger than expected, it does not preclude the possibility that the source is the X-ray counterpart of PSR J1119−6127, especially if other evidence supports the association.

**ROSAT**

Analysis of the ROSAT data is easier, as there is only data from a single camera (PSPC-B). We use the FTOOL `pexmap` to generate an exposure map that accounts for instrumental effects and telescope vignetting. The exposure map was rebinned
by a factor of 2 (15′ pixel\(^{-1}\)) and used to produce flat-fielded images in the standard \textit{ROSAT} soft (0.1 – 0.4 keV) and hard (0.5 – 2.0 keV) bands. X-ray events extracted within a 7′ radius from PSR J1119–6127 were used as input to the \texttt{FTOOL pcrpsf} to estimate the PSF of mirror+PSPC combination, which is well-described by a Gaussian with width \(\sigma = 1.4′\). The flat-fielded images were then smoothed with a slightly smaller Gaussian (\(\sigma = 1.25′\)) to ensure that any small-scale features in the images would be real.

Figure 7-2 shows the resultant images for the soft (\textit{left}) and hard (\textit{right}) bands. Just as the case with the \textit{ASCA} data, a cross marks the position of PSR J1119–6127 and the contours are from the ATCA observations (Crawford 2000; Crawford et al. 2000). No emission from the SNR is detected in the soft band. However, in the hard band, emission coincident with western side of the radio shell is strongly detected. No X-rays are detected from the pulsar in either band. The morphology of the hard \textit{ROSAT} band (0.5 – 2.0 keV; Figure 7-2 [\textit{right}]) agrees very well with that of the soft GIS band (0.7 – 3.0 keV; Figure 7-1 [\textit{middle left}]).

The agreement between the two telescopes offers the chance to check the absolute pointing of \textit{ASCA}. Due to its large FOV (2° in diameter) and its soft-energy sensitivity, the PSPC usually detects emission from several nearby stars in any given pointing. The positions of well-resolved point-sources were checked for optical counterparts using the \texttt{SIMBAD} catalog.\(^4\) Four bright stars were found, and the mean offset between the optical and X-ray positions is 18″. Thus, we take the absolute position uncertainty of these PSPC data to be 18″. Next, we cross-correlated the morphology between the PSPC and GIS data. Unfortunately, the \(~\)arc-minute spatial resolution of both images, combined with the different responses of both instruments, makes a detailed alignment check impossible. While an offset of more than \(~1′\) between the \textit{ASCA} and \textit{ROSAT} observations can be ruled out, this does not represent an improvement to the \textit{ASCA} uncertainty of 0′.5 already discussed.

\(^4\)\url{http://cdsweb.u-strasbg.fr/Simbad.html}. 

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Figure 7-2 *ROSAT* PSPC images of the field around PSR J1119−6127. In each image, the location of PSR J1119−6127 is marked by a cross. The contours are from 20 cm ATCA radio observations and range from 10% to 90% of the maximum value (0.7 mJy beam$^{-1}$) in increments of 10% (Crawford 2000; Crawford et al. 2000). The color bars in each plot indicate counts sec$^{-1}$ arcmin$^{-2}$. *Left:* The soft-band (0.1−0.4 keV) image shows no emission coincident with either the radio contours or the pulsar. *Right:* The hard-band (0.5−2.0 keV) image clearly shows emission from the western side of the SNR and has the same morphology and intensity distribution as the soft-band GIS image (Figure 7-1 [middle left]). No X-ray counterpart to PSR J1119−6127 is visible.

### 7.3.2 Timing Analysis

Pulsations from PSR J1119−6127 were searched for by extracting events from a circular region centered on the position of AX J1119.1−6128.5. After the arrival times were bary centered using the FTOOL `timeconv`, the data were folded into ten phase bins using the post-glitch radio ephemeris corresponding to the mean MJD of the *ASCA* observation. Here, the rotational phase of the pulsar is described by

$$\phi(T) = \nu T + \frac{1}{2} \dot{\nu} T^2 + \frac{1}{6} \ddot{\nu} T^3 + \ldots,$$  \hspace{1cm} (7.1)

where $T$ denotes the pulsar proper time.

The *ASCA* observation of PSR J1119−6127 occurred very close to the time the pulsar glitched (Camilo et al. 2000). Although the X-ray data was apparently taken after
the glitch, the timing data discussed by Camilo et al. (2000) cannot exactly constrain the date of the glitch. Hence, the possibility exists that the pre-glitch ephemeris is the appropriate one to use for the folding. However, given the small differences in the pre- and post-glitch values of $\nu$ and $\dot{\nu}$ and the total length $T$ of the observation, the difference in phase is $\Delta \phi = 1 \times 10^{-3}$. The results are thus insensitive to the actual date of the glitch.

The emission from G292.2$-$0.54 significantly contaminates the signal from AX J1119.5$-$6128.5 and could prevent the detection of X-ray pulsations from PSR J1119$-$6127. To minimize this possibility, we extracted data using combinations of four different aperture radii (ranging between 2$'$ and 5$'$ in increments of one arcmin) and twelve different energy bands (e.g., 0.8$-$10 keV and 1$-$5 keV). Because the SNR and putative pulsar emission have different spectral and spatial properties, one combination of selection criteria should have the highest sensitivity for detecting pulsations. Given the limited statistics of the observation, there is no way to a priori determine the appropriate combination of aperture size and energy band. Instead, all resultant pulse profiles were searched for pulsations using both the $H$-test (de Jager 1994) and $\chi^2$ (Leahy et al. 1983) to search for significance. No pulsation was found in any of the data sets. We derive an upper limit on pulsations by injecting a pulsed signal with duty cycle of 50% into the list of arrival times. Accounting for the background contribution to the total number of counts (see §7.3.1), we adjust the strength of the signal until it is detectable at a significance of $3\sigma$. The upper limits from folding 3$-$10 keV photons within a 3$'$ radius of AX J1119.1$-$6128.5 are typical of all the values. For the $\sim$170 background-subtracted counts ($\sim$650 counts in total), the $3\sigma$ upper limit on pulsations for a 50% duty cycle is greater than 50%.

### 7.3.3 Spectral Analysis

We restrict our spectral work to only the ASCA GIS and ROSAT PSPC data. We define regions where it is appropriate to sum counts together and construct a single spectrum for a given area. One such region is the western side of the SNR, bright in
soft X-rays. We extract a spectrum for both the GIS and PSPC from an ellipse $17' \times 7'$ in extent, with major axis parallel to lines of constant right ascension and centered in the middle of the bright SNR emission. A natural complement to this spectrum is one drawn from the eastern side of the G292.2−0.54. Here, only the GIS, with its high-energy (i.e. $E > 2$ keV) sensitivity, can provide spectroscopic information. In this case, the spectrum is drawn from a crescent-shaped region, slightly larger than the radio shell and excluding the point-source and the western side. Figure 7-3 displays the broad-band GIS (left) and hard-band PSPC (right) images, with the spectrum areas indicated. We also extract a GIS spectrum for the point source from a circular region with radius of 2.5', also shown in Figure 7-3 (left).

Figure 7-3 Broad-band GIS image (left) and hard-band PSPC image (right) around PSR J1119−6127. The position of PSR J1119−6127 is marked by a cross. The black ellipse indicates the region used to extract the “Western side” spectrum, while the crescent-shaped region defined by the largest circle and the partial ellipse indicates that used to extract the “Eastern side” spectrum. The smaller concentric circles indicate the regions used to extract the spectrum of the point source. The inner-most circle defines the source region, while the outer two circles define the background annulus.
The large PSFs of both ASCA and ROSAT results in a contamination of the source flux with diffuse X-ray background (XRB) as well as emission from the SNR. This requires a background spectrum, describing the non-source contribution, to be subtracted from the data to ensure a reliable fit. Ideally, the background should be taken from a nearby region that is source free and located at the same off-axis angle, which not only accounts for the XRB but for any local diffuse emission, always a possibility when looking in the Galactic plane. While this task is trivial for the PSPC and its 2° FOV, the situation is more complicated for the GIS.

While more than 50% of the GIS FOV is unoccupied by G292.2−0.54, this region is not appropriate for extracting a background, as the broad wings and scattering properties of the XRT result in reflection properties that are strongly dependent on both incident energy and off-axis angle (see, e.g., Gendreau 1995). Instead, we use the FTOOL mkgisbgd and the 2.1 Msec of high-latitude data rescreened without using the Risetime parameter (see §7.3.1 for details). In addition to producing a background spectrum with high fidelity (e.g. between 200 – 3000 counts in each GIS channel for the Eastern region), this method inherently accounts for instrument background, as the background events are selected from exactly the same portion of GIS used in extracting the source spectrum. The only potential difficulty with this technique is if local emission is present, specifically in the form of Galactic ridge emission (e.g. Kaneda et al. 1997). However, studies with Exosat show that such emission rapidly decreases for Galactic longitudes $|l| < 40^\circ$ (Warwick et al. 1985). For the region around PSR J1119−6127 ($l = 292^\circ$), no such component should be present.

Once we generated source and background spectra, response functions (detector energy redistribution matrices) were retrieved from HEASARC and ancillary response functions (ARFs; matrices that contain information about the effective area of the mirror and quantum efficiency of the detector) were generated using the FTOOLS ascaarf and pcarf. Initially, we treated the two sides of the G292.2−0.54 separately, jointly fitting the three data sets from the Western Side (GIS-2, GIS-3, and PSPC) and
then independently fitting the two data sets from the Eastern Side (GIS-2 and GIS-3). However, it became clear that regardless of the model used, the only difference between the fit parameters from the two sides (after scaling for differences in sky areas) is in column density $N_H$.

In light of this information, we simultaneously fit all five data sets to a single spectral model. Free parameters are two values of $N_H$ (one for each side), the spectral characterization (e.g. temperature for a plasma model), and three normalization values, two for the Western Side (GIS-2+GIS-3 and PSPC) and one for the Eastern Side (GIS-2+GIS-3). The energy range fit is restricted to those bands where the signal is statistically significant: 0.4 – 2.0 keV (PSPC), 0.7 – 7.0 keV (GIS-Western Side), 0.7 – 8.0 (GIS-Eastern Side). Data were then rebinned such that each background-subtracted energy bin had a minimum of 20 counts, allowing us to use the $\chi^2$ statistic as our goodness-of-fit estimator. All fitting is performed with XSPEC v.10.0 (Arnaud 1996) using standard models.

A search of the literature finds a bevy of different models to characterize emission from SNRs. Here, we use a thermal bremsstrahlung model and the MEKAL\textsuperscript{5} plasma model as representative thermal spectra and a simple power-law to explore non-thermal models. Elemental abundances have been frozen at the values determined by Anders & Grevesse (1989). Table 7-2 lists the results of our fits, including derived parameters and their 90% confidence limits. The measured absorbed fluxes for the Western region are $F_{0.7-7 \text{ keV}} = 2 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$ (ASCA) and $F_{0.4-2 \text{ keV}} = 7 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$ (ROSAT) and for the Eastern region is $F_{0.7-8 \text{ keV}} = 3 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$ (ASCA). Although the power-law model has the lowest $\chi^2$, the $F$-test (see, e.g., Bevington & Robinson 1992) indicates that all three models describe the data equally well. However, the rather large reduced $\chi^2$ values ($\chi^2_{\nu} = 1.6 - 1.7$) indicate an inconsistency between the data and each model.

Figures 7-4 and 7-5 display spectra from different regions of G292.2–0.54, plot-
Table 7-2. Spectral fit parameters for SNR G292.2−0.5

<table>
<thead>
<tr>
<th>Model</th>
<th>$kT$ (keV)</th>
<th>Photon Index</th>
<th>Western Side</th>
<th>Eastern Side</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$N_H$ (10$^{22}$ cm$^{-2}$)</td>
<td>Norm$^a$ (10$^{-3}$)</td>
<td>Norm$^b$ (10$^{-3}$)</td>
</tr>
<tr>
<td>P.L.</td>
<td>⋮</td>
<td>2.3 ± 0.1</td>
<td>0.28$^{+0.07}_{-0.06}$</td>
<td>0.97$^{+0.13}_{-0.11}$</td>
<td>0.62$^{+0.12}_{-0.11}$</td>
</tr>
<tr>
<td>T.B.</td>
<td>4.1$^{+0.6}_{-0.5}$</td>
<td>⋮</td>
<td>0.14$^{+0.05}_{-0.04}$</td>
<td>0.81$^{+0.07}_{-0.06}$</td>
<td>0.51$^{+0.09}_{-0.08}$</td>
</tr>
<tr>
<td>MEKAL</td>
<td>3.5$^{+0.4}_{-0.3}$</td>
<td>⋮</td>
<td>0.16$^{+0.06}_{-0.05}$</td>
<td>2.0 ± 0.1</td>
<td>1.3 ± 0.2</td>
</tr>
</tbody>
</table>

$^a$Parameter for the ASCA (GIS2+GIS3) data.

$^b$Parameter for the ROSAT PSPC data.

Note. — P.L. refers to power law, T.B. to thermal bremsstrahlung. Norm refers to the normalization used for a particular model: power law—(photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$), thermal bremsstrahlung—($\int n_e n_f I dV$, or MEKAL—($\int n_e n_H I dV$). All uncertainties represent the 90% confidence limits.
Figure 7-4 ASCA GIS and ROSAT PSPC spectra of G292.2−0.54. The solid lines represent the best-fit MEKAL models for the data. The PSPC (top) and GIS (middle) spectra from the western side of the SNR are very soft compared to the highly absorbed GIS spectrum (bottom) of the eastern side. Both the MEKAL and power-law spectral models describe the data equally well. The data in black are from GIS–2, while the data in red are from GIS–3.
Figure 7-5 ASCA GIS and ROSAT PSPC spectra of G292.2–0.54. The solid lines represent the best-fit power-law models for the data. The PSPC (top) and GIS (middle) spectra from the western side of the SNR are very soft compared to the highly absorbed GIS spectrum (bottom) of the eastern side. Both the MEKAL and power-law spectral models describe the data equally well. The data in black are from GIS–2, while the data in red are from GIS–3.
ted with the best-fit MEKAL and power-law models, respectively. For clarity, we present the data for a given region and instrument separately: PSPC western side (top), GIS western side (middle), GIS eastern side (bottom). The large χ² is mainly attributable to systematic errors in the fit, easily seen in the residuals below 2 keV in the spectra from the western side and above 5 keV in the spectra from the eastern side. Attempts to improve the fit by addition of a second spectral component do not work for two reasons. First, while some of the excesses (i.e. Model/Data > 1) appear to be emission-like features, there are no known lines at these energies. (For the same reason, adjusting the elemental abundances in the MEKAL model does not improve the fit.) Second, although the approximately 1000 counts in each GIS spectrum and the 500 counts in the PSPC spectrum allow a fairly tight constraint on a single model, there is not sufficient data to fit a combination of two models. Inevitably, the best-fit parameters for the additional component tend towards the limits of the parameter space and resulted in unphysical values (i.e. normalizations of order 10⁻¹⁰ to 10⁻¹² or temperatures of only a few eV).

AX J1119.1−6128.5

A serious challenge in fitting the spectrum of the point source is the relatively low number of source photons (173 background-subtracted counts between 0.7−5 keV). Given that it is not detected with ROSAT nor in the soft-band of the GIS, this source must either be intrinsically hard (e.g., temperature of several to tens of keV) or highly absorbed. With three times more events in the 2−5 keV band than in the 0.7−2 keV band and very few events above 5 keV, either scenario is plausible.

Due to the limited statistics, it is impossible to fit the spectrum if all three parameters (N_H, kT or Γ, and normalization) are allowed to vary. (The strong co-variance between the parameters results in a degeneracy effectively the size of the entire parameter space.) Instead, we only require 10 background-subtracted counts per energy bin and fix the column at N_H = 1.5 × 10²² cm⁻², the value determined using the MEKAL model for the eastern side of G292.2−0.54. While these modifications to the fitting
scheme, compared to those used for G292.2−0.54, introduce additional uncertainty, it does allow at least a coarse characterization of the spectral nature of the point source.

For a power-law model, the photon index is $\Gamma = 1.4^{+1.0}_{-1.2}$ and the normalization is $(8 \pm 8) \times 10^{-5}$. For a thermal bremsstrahlung model, the temperature is $kT = 13^{+\infty}_{-11}$ keV and the normalization is $(1^{+0.9}_{-0.3}) \times 10^{-5}$. (Here, the upper limit on $kT$ reflects the lack of ASCA's response above 10 keV. Refer to Table 7-2 for the normalization units). The measured absorbed flux is $F_{0.7-5 \text{ keV}} = 2 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$.

Our decision not to undertake analysis of the ASCA SIS data is motivated by several factors. First, radiation damage has greatly reduced the performance of the SIS. While the SIS initially had the best energy resolution of the three instruments, at the time these data were acquired, this was no longer true. Second, reduction of spectroscopic SIS data requires the use of several phenomenological models to account for radiation-induced effects. Though these have proved useful, the lack of an underlying physical model and unaccounted-for effects make any analysis suspect. For example, Ueda et al. (1999) have found that the absolute detection efficiency of the SIS, normalized to the GIS, decreased monotonically from 12% to 18% over an 18 month span they studied. Finally, the smaller FOV of the SIS only encompasses $\sim 60\%$ of the SNR area, with a sizable fraction of the bright western region falling off the CCDs. Hence, for this observation, the SIS cannot provide any additional information not already present from analysis of the more reliable GIS and PSPC data.

7.4 Discussion

7.4.1 General properties of G292.2−0.54

One of the main arguments supporting the interpretation of the extended emission as an SNR is its correlation with the morphology of the radio shell, recently shown to have radio spectral properties consistent with other known SNRs (Crawford 2000;
The presence of PSR J1119–6127 in the middle of the radio and X-ray emission not only strengthens this reasoning, it provides a way to test the consistency of the claimed association. For if PSR J1119–6127 and G292.2–0.54 are the remnants of the same supernova, the age of the SNR must be that of the pulsar and its properties should be those of a young remnant.

It is common to estimate the pulsar’s age with the characteristic age \( \tau_c \). In most circumstances, when \( \tau_c \) is used there is a risk of greatly underestimating the pulsar’s age, since \( \tau_c \rightarrow \infty \) as \( n \rightarrow 1 \) (see Equation 6.9). Fortunately, this is not a concern for PSR J1119–6127 as the braking index is in fact measured to be 2.9 and \( \tau_c = 1600 \) years. Of course, if the current spin period is still close to that of the initial period, then \( \tau_c \) will over-estimate the age of pulsar. Thus, \( \sim 1600 \) yr represents a hard upper limit.

Our next step is to determine the distance of the system. One such estimate comes from the Taylor & Cordes (1993) DM-distance relationship. However, the dispersion measure of PSR J1119–6127 (DM = 707 pc cm\(^{-3}\)) implies a distance of more than 30 kpc, well outside of the Galaxy! This spuriously large value is easily understood, as the Galactic longitude of PSR J1119–6127 (\( l = 292^\circ \)) is nearly tangential to the Carina spiral arm, intersecting it at distance of 2.4 and 8.0 kpc.

The best explanation for the large DM measured is that there must be clumping of dense, dispersive material in the direction of the pulsar. The Taylor & Cordes model, which lacks fine structure (i.e. small-scale clumps), simply underestimates the electron density, and hence overestimate the distance, for this particular line-of-sight. Fortunately, a reasonable upper limit on the distance can be obtained by assuming that PSR J1119–6127 lies no further than the second intersection point or 8 kpc. We also note that in this particular direction, the edge of the Galaxy only extends \( \sim 10 \) kpc from the Sun (Georgelin & Georgelin 1976; Taylor & Cordes 1993), limiting the maximum error in the distance to 25%.

The diameter of G292.2–0.54 extends \( \sim 14' \) in radio and \( \sim 17' \) in X-rays. The slightly larger extent in the X-rays may either be real or an artifact of the larger
PSFs of ASCA and ROSAT, compared to the ATCA beamsize. We adopt an angular size of \((15 \pm 2)\)' to encompass both measurements. Taken with the age and distance estimates, we calculate a mean expansion velocity of \(v = (10 \pm 1.4)D_8 \times 10^3 \text{ km s}^{-1}\), where \(D_8\) is the distance to the pulsar parameterized in units of 8 kpc. This velocity is consistent for that of a 1600 yr old SNR still evolving in the free expansion phase. It implies a kinetic energy for the initial explosion of \(E_{51} = (1 \pm 0.3)M_{\text{ej}} D_8^2\), where \(E_{51}\) is the explosion energy in units of 10\(^{51}\) ergs and \(M_{\text{ej}}\) is the ejected mass in units of solar masses \(M_\odot\).

Of course, G292.2–0.54 may also be in the Sedov-Taylor (ST) phase. For adiabatic expansion, \(r_{\text{SNR}} = 1.15(Et^2/\rho)^{1/5}\) (Taylor 1950; Sedov 1959), where \(r_{\text{SNR}}\) is the linear radius of the SNR, \(E\) is the explosion energy, \(t\) is the SNR’s age, and \(\rho\) is the mass density. Using the measured size of the SNR and recasting in terms of the ambient particle density \(n\) into which the SNR is expanding, \((E_{51}/n) = (130 \pm 80)D_5^2\). Remnants only enter ST evolution after sweeping up 20 times their ejected mass \(M_{\text{ej}}\) (Fabian, Brinkmann, & Stewart 1983; Dohm-Palmer & Jones 1996). We approximate the material swept up by the SNR by assuming a constant density \(\rho = nm_{\text{H}}\) inside the volume occupied by G292.2–0.54; this requires \(n > (0.04 \pm 0.02)M_{\text{ej}} D_8^{-3} \text{ cm}^{-3}\). Substituting into the expression determined for the ratio of explosion energy to particle density \((E_{51}/n)\) requires \(E_{51} > (5 \pm 4)D_8^2 M_{\text{ej}}\), where \(M_{\text{ej}}\) is again expressed in terms of solar masses \(M_\odot\).

The implied ratio \((E_{51}/M_{\text{ej}})\) is as much as one hundred times higher than those found for most young Galactic SNRs (see, e.g., Smith 1988). We note that the only other well-documented large value for \((E_{51}/M_{\text{ej}})\) is for G320.4–01.2, the SNR associated with PSR B1509–58 (Gaensler et al. 1999 and references therein). This correlation further strengthens the argument that PSR J1119–6127 belongs to a class of pulsars typified by PSR B1509–58. It also raises the possibility that their unusual properties (i.e. large magnetic field and rapid spin-down rate) may be partially explained by an common evolutionary scenario. For example, Gaensler et al. (1999) suggest that the progenitor of PSR B1509–58 was a massive star that later evolved
into a helium star before it underwent a supernova.

7.4.2 X-ray properties of G292.2−0.54

Spectrum

At first, one of the most surprising aspects of the spectrum is the lack of obvious line features commonly seen in young SNRs like Cas A (e.g., Hughes et al. 2000), Tycho (Hwang & Gotthelf 1997), MSH 15−52 (e.g., Tamura et. al 1996), and Puppis A (Winkler et al. 1981; Berthiaume et al. 1994). However, from the MEKAL fits (Figure 7-4), it is clear that after this line-rich spectrum is folded through the GIS response, the only lines that should be visible are possibly the Fe K species around 6.7 keV. In fact, the residuals above 6 keV are smaller for the MEKAL model (Figure 7-4 [bottom]) than for the power-law model (Figure 7-5 [bottom]), indicating that these lines may be present.

One difficulty with either of the thermal models is the large derived temperatures of $kT \approx 4$ keV. Typically, even young remnants with ages less than 1000 yr have temperatures closer to 2 keV (Koyama et al. 1996 and Sakano et al. 1999). One plausible explanation for this apparent discrepancy is the use of a simple plasma model assuming solar elemental abundances. In most cases, SNR spectra with sufficiently high counting statistics (a minimum of several thousand source counts) or high energy resolution ($E/\Delta E$ of several hundred, as in the case of the Focal Plane Crystal Spectrometer on Einstein) require non-solar abundances and at least one non-equilibrium ionization (NEI) model to properly describe the data (e.g., Hughes et al. 2000, Winkler et al. 1981, and Hayashi et al. 1994).

While the lack of any obvious line features prevents us from attempting to fit more realistic models, we explored this possibility by adjusting the abundances of the three metals with the largest number densities relative to H, namely Si, S, and Fe. Table 7-3 lists the best-fit MEKAL temperatures obtained when the abundances have been multiplied by factors of 1.5, 2.0 and 3.0. As the amount of metals is increased, the
temperature monotonically drops from $3.5^{+0.4}_{-0.3}$ keV to $2.8 \pm 0.2$ keV. The goodness of fit ($\chi^2$) also grows, as do the systematic residuals, indicating that abundances factors of five to ten greater than solar are ruled out. However, it is quite realistic to expect that the use of a NEI model in conjunction with modestly-enriched abundances would result in a goodness of fit comparable to that of the power-law or MEKAL model.

The spectral fitting we performed also allows the intriguing possibility that the emission from G292.2−0.54 is non-thermal in origin. It is well-established that most young SNRs have a strong non-thermal component (see Allen, Gotthelf, & Petre [1999] for a recent review). In the most commonly accepted scenario, electrons are accelerated by the remnant’s shock wave to energies of $\sim$1 TeV and emit high-energy radiation via the synchrotron mechanism (e.g., Reynolds 1998). Usually, though, thermal X-rays are also present in the SNR. The notable exception is SNR G347.3−0.5, which shows no measurable thermal emission down to very low limits (Slane et al. 1999). The photon index $\Gamma$ measured for G292.2−0.54 ($2.3 \pm 0.2$) agrees very well with those reported from different regions of G347.3−0.5 ($2.2, 2.4, \text{ and } 2.4$). This spectrum is distinctly harder than those of SNRs that exhibit both thermal and non-thermal emission, like Cas A ($3.0 \pm 0.2$), SN 1006 ($3.0 \pm 0.2$), Kepler ($3.0 \pm 0.2$), Tycho ($3.2 \pm 0.1$), and RCW 86 ($3.3 \pm 0.2$) (Allen et al. 1997; Allen et al. 1999; Allen, Gotthelf, & Petre 1999).

While the spectral similarities support the idea that G292.2−0.54 may belong to a class of non-thermal remnants typified by G347.3−0.5, they are equally compelling reasons that weaken this line of reasoning. Slane et al. (1999) show that the properties of G347.3−0.5 can reasonably be explained if the remnant is in a well-advanced Sedov evolutionary phase and has an age between 19 − 41 kyr. This is in striking contrast to G292.2−0.54, which is extremely young and is (possibly) just entering the Sedov phase. Ultimately, the nature of G292.2−0.54, be it a typical young thermal SNR or a more exotic manifestation of the SNR phenomena, will only be decided with additional observations.
Table 7-3. X-ray temperature dependence on elemental abundances

<table>
<thead>
<tr>
<th>$kT$ (keV)</th>
<th>Abundance factor</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.5^{+0.4}_{-0.3}$</td>
<td>1.0</td>
<td>351/211</td>
</tr>
<tr>
<td>3.4 ± 0.3</td>
<td>1.5</td>
<td>376/211</td>
</tr>
<tr>
<td>3.1 ± 0.3</td>
<td>2.0</td>
<td>410/211</td>
</tr>
<tr>
<td>2.8 ± 0.2</td>
<td>3.0</td>
<td>479/211</td>
</tr>
</tbody>
</table>

Note. — Here, only the most common heavy elements (Si, S, and Fe) have had their abundances, as determined by Anders & Grevesse (1989), multiplied by this factor.
Another important aspect of the spectrum that requires explanation is the lack of soft X-rays from the eastern side of G292.2−0.54 (Figure 7-1 [middle row] and Figure 7-2) and the rather uniformly filled morphology at high energies (Figure 7-1 [bottom row]). This absence manifests itself via absorption of emission below \( \sim 1.5 \) keV (Figure 7-4 and 7-5 [bottom]). Again using SIMBAD, we looked for objects in the vicinity of PSR J1119−6127 that might account for the absorption. A likely candidate is Dark Cloud DC 292.3−0.4, catalogued by Hartley et al. (1986) during a systematic search of ESO/SERC Southern J survey plates for optically identified dark clouds. Their work is an extension of the seminal work by Lynds (1962) to declinations south of \(-35^\circ\). Hartley et al. (19866) approximate the shape and size of each cloud with an ellipse and use three classes to characterize the density of each cloud. (N.B. the reported dimensions do not necessarily reflect the shape of the cloud [e.g., if the cloud is elongated or curved], but do give an accurate estimate of the total area the cloud occupies.)

DC 292.3−0.4 is described by an ellipse with major and minor axes of 16′. In Figure 7-6, we overlay the dark cloud, represented by a hatched-circle with diameter 16′, on the hard-band PSPC image (left) and soft-band GIS image (right). DC 292.3−0.4 appears to be located at a position capable of obscuring the eastern side of G292.2−0.54, and given that the cloud is certainly not spherical, it seems quite plausible that substructure (e.g., a finger or wisp) extending across the SNR absorbs the soft X-ray emission.

A more quantitative check is to see if the cloud can account for the difference in column densities \( N_H = 1.3 \times 10^{22} \) cm\(^{-2}\) between the two sides of the SNR. The cloud’s density (class B) roughly equals the Lynds designation of opacity class (OC) 4 or 5, which, using the calibrated relationship of Feitzinger and Stüwe (1986), \( A_V = 0.70 \) OC+0.5 mag, gives an extinction \( A_V = 3.3−4.0 \) from DC 292.3−0.4. The corresponding column density \( N_H \) can be estimated using \( N_H = 1.7 \times 10^{21} A_V \) cm\(^{-2}\) mag\(^{-1}\), derived from \( \langle N(\text{H}i)/E(B−V) \rangle = 5.2 \times 10^{21} \) cm\(^{-2}\) mag\(^{-1}\) (Shull & van Steenberg...
Figure 7-6 Soft-band GIS image (left) and hard-band PSPC image (right) of G292.2−0.54. The large hatched circle represents the approximate shape of dark cloud DC 292.3−0.4, which we suggest accounts for a large part of the absorption of soft X-rays from the eastern side of the SNR. The pulsar location is marked by a cross. The star marks the location of HD 306313, a B9 star that is positional coincident with enhancements in emission from the western side of the remnant in both detectors. In each image, contours span between 35% – 95% of the maximum flux in increments of 10%.

1985) and \[\frac{A(V)}{E(B - V)} = 3.1\] (Cardelli, Clayton, & Mathis 1989). Thus, we expect DC 292.3−0.4 to contribute \((6–7) \times 10^{21}\) cm\(^{-2}\) to the eastern side of G292.2−0.54, or roughly half of the additional amount of \(N_H\) present on this side of the SNR.

The presence of DC 292.3−0.4 also offers the chance to probe the distance to PSR J1119−6127. Recently, Otrupcek, Hartley & Wang (2000) observed the 115 GHz (J=1-0) transition of CO towards the center of each cloud in the Hartley et al. catalog. Two features with line of sight velocities of −12.6 km s\(^{-1}\) and 1.6 km s\(^{-1}\) were detected for the cloud. Adopting the method of Gaensler et al. (1999), these velocities correspond to minimum distances of −0.2 and 1.7 kpc and maximum distances of 4.7 and 6.6 kpc. The low FHWM measured for these features, combined with the fact that any cloud optically identified is inherently close, indicates that DC 292.3−0.4 must be no further than a few kpc. Unfortunately, with no way to discern which feature corresponds to the cloud, these CO measurements cannot provide an interesting lower
limit for the pulsar’s distance. The presence of two features is encouraging, as it suggests an additional cloud is present along the line of sight and contributes to the absorption of soft X-rays from the eastern side of G292.2−0.54.

Figure 7-6 also shows the location of HD 306313, a B9 star with apparent magnitude 11.6. Until recently, late B stars were not thought to have high energy emission. However, analysis of the ROSAT all-sky survey revealed that these stellar types can in fact be X-ray bright (Berghöfer & Schmitt 1994; Berghöfer, Schmitt, & Cassinelli 1996). While only 10% of B9 stars emit X-rays (Berghöfer et al. 1997), this offers a possible explanation for the flux enhancements in both the PSPC and GIS images near the star. The USNO-A2.0 catalog of stars gives a blue magnitude of 12.7 and a red magnitude of 11.6 for HD 306313. The USNO calibration algorithms\(^6\) allow us to convert to standard \(B\) and \(V\) colors, and assuming a magnitude uncertainty \(\sigma = 0.25\) (Grazian et al. 2000) and correcting for the intrinsic color of a B9 star, we calculate color excesses \(\langle E(B − V)\rangle\) for several stellar classes (i.e. I, III, V). Finally, adopting the absolute magnitudes measured by Jaschek & Gómez (1998) for B9 stars and the reddening law used above, we derive distances of 250 ± 80 pc (B9 V), 550 ± 165 pc (B9 III), and 6.3 ± 3.5 kpc (B9 I).

As the PSPC flux (see below) from the entire western region totals \(7 \times 10^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\), we estimate the star would only need to have 1−10% of this flux to be observable. The X-ray luminosity in the 0.1–2.4 keV band for B9 stars ranges between \(\log (L_x) = 28.5 − 31.0\) (Berghöfer 1997). While the low flux precludes emission from a distant (i.e. more than a few kpc) supergiant is ruled out, a main sequence or giant star, with maximum unabsorbed fluxes of \(1.3 \times 10^{-12}\) and \(2.8 \times 10^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\), could easily result in the bright feature visible in the hard-band PSPC and soft-band GIS data. Moreover, stellar emission contamination of the SNR spectrum would also explain the systematic residuals seen below 2 keV. In a detailed spectral study of A0–F6 stars, Panzera et al. (1999) show that these stars are best described by a

\(^{6}\)http://www.nofs.navy.mil/
combination of two Raymond-Smith plasma models with average temperatures of \( \langle kT \rangle \sim 0.7 \text{ keV} \) and \( \langle kT \rangle \sim 0.2 \text{ keV} \). We tried adding a Raymond-Smith component to our best-fit models, but for the reasons stated in §7.3.3, these attempts were unsuccessful.

We conclude with an intriguing possibility to be pursued in future observations. If HD 306313 is confirmed as an X-ray source, with sufficient data its spectral properties can be determined. By comparing its column density with that measured for the western side of G292.2–0.54, a very constraining upper or lower limit to the pulsar/remnant system can be obtained.

**X-ray luminosity**

Table 7-4 presents the flux measured from each side of G292.2–0.54 for each spectral model and each instrument. Luminosities have been calculated assuming a distance of 8 kpc and correcting for the effects of interstellar absorption. Formal errors on \( L_x \) are of order 5%, and regardless of the spectral model, the luminosities for a given region and instrument are within 20% of one another, guaranteeing an excellent measurement of the total luminosity from G292.2–0.54. While the ROSAT-measured luminosities are consistently lower than those of ASCA, this is easily understood given the uncertainties in calibration and differences in telescope sensitivities. The ratio between eastern and western side luminosities from ASCA is \( 2.0 \pm 0.2 \), in excellent agreement with the 2.1 ratio of geometric areas of each region (see Figure 7-3 [left]). The total 0.5–10 keV luminosity from G292.2–0.54 is \( (7 - 9) \times 10^{35} \) ergs s\(^{-1}\).

### 7.4.3 AX J1119.1–6128.5

Figure 7-7 shows a close-up of the GIS hard-band field surrounding PSR J1119–6127. The radio position of PSR J1119–6127 is marked by a cross, while an ellipse (semi-major axis 53\( '' \), semi-minor axis 3\( '' \)) shows the 95% confidence uncertainty position of the unidentified IRAS point-source IRAS J11169–6111. The position of
Table 7-4. X-ray flux and luminosity for SNR G292.2−0.5

<table>
<thead>
<tr>
<th>Spectral model</th>
<th>Western Side</th>
<th>ROSAT</th>
<th>Eastern Side</th>
<th>ASCA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASCA ( P)</td>
<td>L(x)</td>
<td>ASCA ( P)</td>
<td>L(x)</td>
</tr>
<tr>
<td></td>
<td>(10(^{-12}))</td>
<td>(10(^{35}))</td>
<td>(10(^{-12}))</td>
<td>(10(^{35}))</td>
</tr>
<tr>
<td>Power law</td>
<td>2.4</td>
<td>2.9 ± 0.2</td>
<td>0.67</td>
<td>1.8(^{+0.3}_{-0.2})</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>6.0(^{+0.3}_{-0.2})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal brems.</td>
<td>2.4</td>
<td>2.4(^{+0.2}_{-0.1})</td>
<td>0.68</td>
<td>1.5(^{+0.3}_{-0.2})</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>4.6 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEKAL</td>
<td>2.4</td>
<td>2.4 ± 0.1</td>
<td>0.66</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>5.1 ± 0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. — All fluxes, in units of \((\text{ergs s}^{-1} \text{ cm}^{-2})\), refer to the measured absorbed flux for the given energy band. All luminosities, in units of \((\text{ergs s}^{-1})\), are for the 0.5 – 10 keV passband. They have been corrected for absorption and assume a distance of 8 kpc. All uncertainties represent the 90% confidence limits.
the IRAS source (α (J2000) = 11$^h$ 19$^m$ 7.05, δ (J2000) = −61° 27′ 26″3) is offset 68″ from AX J1119.1–6128.5. (Recall that PSR J1119–6127 is offset 82″ from AX J1119.1–6128.5.) While the position of IRAS J11169–6111 has a large uncertainty and is slightly closer to the ASCA source than PSR J1119–6127, the offsets are too large to claim that AX J1119.1–6128.5 is the X-ray counterpart of the pulsar or IRAS source based solely on positionally coincidence. Below, we consider additional evidence that supports either scenario.

Figure 7-7 Hard-band (3 − 10 keV) ASCA image of the immediate region around AX J1119.1–6128.5. A dark cross marks the location of PSR J1119–6127, while a dark ellipse (semi-major axis 53″, semi-minor axis 3″) marks the 95% confidence position of IRAS J11169–6111. Contours correspond to 35 − 95% of the maximum flux in increments of 10%.

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X-ray Luminosity

The small number of counts from the point source precludes determining the nature of the underlying emission mechanism (e.g. thermal or non-thermal). However, by deriving the luminosity implied for various spectral models, it is possible to check the consistency of the assumption. All the luminosities reported below assume a distance of 8 kpc and have been corrected for the effects of interstellar absorption. In the case when both the photon index and normalization were allowed to vary, the implied luminosity in the $0.1 - 2.4$ keV band is $(2_{-2}^{+7}) \times 10^{33}$ ergs s$^{-1}$, while in the $0.5 - 10$ keV band it is $(5_{-5}^{+64}) \times 10^{33}$ ergs s$^{-1}$. The huge spread is due to the large uncertainty in the photon index (recall $\Gamma = 0.2 - 2.4$). When the photon index is fixed at the canonical value for young pulsars ($\Gamma = 2$), the luminosity range narrows dramatically to $(5 \pm 2) \times 10^{33}$ ergs s$^{-1}$ for both the $0.1 - 2.4$ and $0.5 - 10$ keV bands. For the thermal bremsstrahlung model, the formal confidence limit on the temperature is $kT = 13_{-11}^{+\infty}$ keV. If we estimate the upper-limit at $kT = 20$ keV, the luminosity in the $0.1 - 2.4$ keV band is $(2 \pm 1) \times 10^{33}$ ergs s$^{-1}$, while in the $0.5 - 10$ keV band it is $(4_{-3}^{+4}) \times 10^{33}$ ergs s$^{-1}$. Thus, for either the thermal or non-thermal model, the luminosity for AX J1119.1–6128.5 in either commonly-reported band (0.1 – 2.4 or 0.5 – 10 keV) is $\sim (1 - 5) \times 10^{33}$ ergs s$^{-1}$.

An Unresolved Synchrotron Nebula?

If AX J1119.1–6128.5 truly has a non-thermal spectrum described by a relatively flat power law (i.e. $\Gamma \lesssim 2$), the implied X-ray luminosity is consistent with the interpretation that it is the X-ray counterpart to PSR J1119–6127. First, we consider the luminosity with a fixed photon index $\Gamma = 2$. The conversion efficiency $\dot{E}$ into $L_x$ is $\epsilon \equiv (L_x/\dot{E}) = (3 \pm 1) \times 10^{-3}$ for both the ROSAT (0.1 – 2.4) and Einstein (0.2 – 4.0) keV bands. These values are very close to those predicted by both the Becker & Trümper (1997 [$\epsilon = 1 \times 10^{-3}$]) and Seward & Wang (1988 [$\epsilon = 4 \times 10^{-3}$]) $L_x - \dot{E}$ relationships. However, this apparently excellent agreement must be viewed cautiously for three reasons. First, from the discussion in §6.6.4, we have shown
that both of these *empirical* relationships have inherent scatter of at least a factor of 4. Second, we have assumed a distance of 8 kpc for PSR J1119–6127. Although it is unlikely that the pulsar is further away or any nearer than 2.4 kpc, a closer distance could lower $L_x$ by as much as a factor of 10, decreasing $\epsilon$ by a similar amount. Finally, we also note that the uncertainty in $\epsilon$ greatly increases when we consider the luminosities derived from the spectral fits where both the normalization and spectral index were free parameters. More than the specific value of $\epsilon$ or whether it agrees well with a particular $L_x - \dot{E}$ prediction is the order of magnitude value: converting one part in a thousand of $\dot{E}$ into X-rays is entirely consistent with the majority of X-ray detected rotation-powered pulsars. If the pulsar is powering the observed high-energy emission, the lack of pulsations coupled with the point-like nature of the source argues that AX J1119.1–6128.5 is an unresolved synchrotron nebula powered by PSR J1119–6127. This is exactly analogous to the X-ray emission observed by *ASCA* from PSR B1046–58 (see Chapter 6).

**A Precursor LMXB?**

If the *ASCA* source has a hard ($kT > 2$ keV) thermal spectrum, no theoretical model nor previous observational evidence supports interpreting AX J1119.1–6128.5 as the counterpart to PSR J1119–6127. More likely, especially given the point-like nature of the *ASCA* source, the emission from AX J1119.1–6128.5 results from accretion onto a compact object. This scenario is strengthened by the presence of IRAS J11169–6111, an infra-red point-source. Recently, two different collaborations have studied this object because of its spatial coincidence with a known S star, red giants similar to M-class giants with prominent ZrO bands.

Chen, Gao & Jorissen (1995) claim that IRAS J11169–6111 is actually a blend of three sources. Lloyd Evans & Little-Marenin (1999) discovered two “very red” objects at the IRAS position, although their observations resolved only a single object at the telescope. They re-classify the (possibly) composite spectrum as M3. Although isolated late-type stars can emit X-rays, their spectra are very soft ($kT < 0.5$ keV)
(Hünsch et al. 1998 and references therein) and cannot explain the emission from AX J1119.1−6128.5. Late-type giants, including M and S stars, in binary systems with white-dwarfs can have slightly harder spectra, with $kT$ approaching $\sim$1 keV (Jorissen et al. 1996; Hünsch et al. 1998), although such a system would still not be hard enough to explain the ASCA source. Even if this star had unprecedented hard emission similar to AX J1119.1−6128.5, it would also require that the ratio of X-ray flux to bolometric flux be several orders of magnitude higher than all other known X-ray-bright M stars (Hünsch et al. 1998). A much more plausible explanation is provided by the hard X-ray emitter 2A 1704+241 (4U 1700+24).

This X-ray source was first identified in the Ariel V 2A catalog (Cooke et al. 1978) and reconfirmed in the fourth Uhuru catalog (Forman et al. 1978). Using data from Einstein and HEAO–1, Garcia et al. (1983) found the spectrum well-described by a highly absorbed ($N_H \sim 10^{22}$ cm$^{-2}$), hard ($kT = 15$ keV) thermal bremsstrahlung model and a $2−11$ keV luminosity between $10^{33}−10^{34}$ ergs s$^{-1}$. They also identified the M3 giant HD 154791 as its optical counterpart.

More recently, Gaudenzi & Polcaro (1999) performed detailed optical spectroscopy of this system and use their results to hypothesize that the observed X-ray emission is powered by accretion onto a neutron star. Moreover, they claim that this system is in the process of evolving into a normal LMXB. Dal Fiume et al. (2000) present recent ASCA and Beppo-SAX observations of 4U1700+24. In agreement with the results of Garcia et al. (1983), they find that the emission is best described with a thermal bremsstrahlung model, although with lower temperatures of $kT = 6.3$ keV and $kT = 3.6$ keV for ASCA and BeppoSAX, respectively. They also show that during both the ASCA and Beppo-SAX, each of which spans 40 ks, the source experienced variability by a factor of two. Equally intriguing, the time-averaged luminosities derived for the ASCA and BeppoSAX observations varied by nearly a factor of three. In contrast to Gaudenzi & Polcaro (1999), Dal Fiume et al. (2000) claim that the X-ray emission is powered by accretion from the M3 giant onto a white dwarf. Whatever the nature of compact object, a similar scenario of accretion from IRAS J11169−6111

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onto a neutron star or white dwarf could explain both the luminosity and spectrum of AX J1119.1−6128.5. In this case, the X-ray binary is completely unrelated to PSR J1119−6127. If the compact object is a white dwarf, the binary is also unrelated to G292.2−0.54. However, if it the compact object is a neutron star, G292.2−0.54 may be related to either AX J1119.1−6128.5 or PSR J1119−6127.