A SHELL OF THERMAL X-RAY EMISSION SURROUNDING THE YOUNG CRAB-LIKE REMNANT 3C 58

E. V. GOTHELFF, D. J. HELFAND, AND L. NEWBURGH
Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027; eric@astro.columbia.edu

Received 2006 July 6; accepted 2006 August 30

ABSTRACT

Deep X-ray imaging spectroscopy of the bright pulsar wind nebula 3C 58 confirms the existence of an embedded thermal X-ray shell surrounding the pulsar PSR J0205+6449. Radially resolved spectra obtained with the XMM-Newton telescope are well characterized by a power-law model with the addition of a soft thermal emission component in varying proportions. These fits reproduce the well-studied increase in the spectral index with radius attributed to synchrotron burn off of high energy electrons. Most interestingly, a radially resolved thermal component is shown to map out a shell-like structure ≈6′ in diameter. The presence of a strong emission line corresponding to the Ne IX He-like transition requires an overabundance of ≈3 × (Ne/Ne) in the Raymond-Smith plasma model. The best-fit temperature kT ≈ 0.23 keV is essentially independent of radius for the derived column density of NH = (4.2 ± 0.1) × 1021 cm−2. Our result suggests that thermal shells can be obscured in the early evolution of a supernova remnant by nonthermal pulsar wind nebulae emission; the luminosity of the 3C 58 shell is more than an order of magnitude below the upper limit on a similar shell in the Crab Nebula. We find the shell centroid to be offset from the pulsar location. If this neutron star has a velocity similar to that of the Crab pulsar, we derive an age of 3700 yr and a velocity vector aligned with the long axis of the PWN. The shell parameters and pulsar offset add to the accumulating evidence that 3C 58 is not the remnant of the supernova of CE 1181.

Subject headings: pulsars: general — stars: individual (PSR J0205+6449, 3C 58) — stars: neutron — X-rays: stars — supernova remnants

1. INTRODUCTION

A long-standing puzzle in supernova physics is the apparent lack of an associated thermal shell surrounding a few young pulsars with bright relativistic wind-powered nebulae. Although relatively rare, with fewer than 10 examples known, the lack of a supernova remnant shell is at odds with our current understanding of supernova evolution and neutron star formation. The canonical examples, the Crab and 3C 58, are both putative historical remnants less than 1000 yr old. To date, no evidence has been found for thermal emission associated with the Crab Nebula pulsar despite repeated searches (Seward et al. 2006 and references therein). However, recent XMM-Newton and Chandra observations have identified thermal emission within the 3C 58 remnant (Bocchino et al. 2001; Slane et al. 2004). The availability of a large quantity of XMM-Newton archival data on this source derived from calibration observations allows us to construct very sensitive images and spectra to explore the evidence for a surrounding supernova remnant (SNR) shell with unprecedented sensitivity.

The morphology of 3C 58 is well documented in both the X-ray and radio bands (Slane et al. 2004; Bietenholz et al. 2006 and references therein). It is center filled with a 66 ms pulsar near the center, axisymmetric lobes, and an elaborate network of wisps and filaments. Failure to find a radio shell around 3C 58 led Reynolds & Aller (1985) to conclude that there is no evidence for its interaction with an external medium. Coupled with the low velocities of the optical filaments (Fesen 1983) compared to the mean expansion velocity required for the remnant to reach its current extent in 820 yr, these results led to suggestions that the remnant was considerably older. Over the past 20 yr, further evidence has accumulated that the remnant’s age is inconsistent with an origin in SN 1181. The images and spatially resolved spectra we present below add incrementally to the case and provide a testable prediction concerning the pulsar velocity, which could support or refute the historical association.

In § 2 we describe the available observations and discuss their analysis. Section 2.4 presents the detailed spatially resolved spectroscopy that allows us to detect clear evidence for a shell of thermal emission, overabundant in neon, and extending to the edge of the synchrotron nebula; we interpret this result in § 3, concluding that the pulsar is offset from the center of the symmetrically expanding shell, implying a velocity aligned with the symmetry axis of the remnant. If the pulsar has a Crab-like velocity, this offset provides another argument against an association with SN 1181.

2. OBSERVATIONS AND RESULTS

2.1. The Observations

A total of 10 pointed observations of 3C 58 are available in the public archive of data obtained with the XMM-Newton X-ray observatory (Jansen et al. 2001). Of these, a set of eight pointings, acquired on 2002 September 11–13 to perform an in-orbit calibration of the telescope mirror vignetting function (Lumb et al. 2004), used imaging modes with a sufficiently large field of view to cover freely the 3C 58 nebula. The duration of these observations varied between 17 and 33 ks. An observation log is presented in Table 1.

In this study we concentrate on data obtained with the European Photon Imaging Camera (EPIC; Turner et al. 2003), which consists of three CCD cameras, the EPIC pn and the two EPIC MOS imagers. The EPIC MOS cameras were operated in Full Frame mode mode, in which the full 30′ diameter field of view is read out every 2.7 s. The EPIC pn was operated in Prime Large Window mode, which provides 78 ms time resolution over a 6.9′ × 13.5′ field of view. For all observations, the thin transmission filter was placed in the focal plane. The EPIC instruments are sensitive to X-rays in the 0.2–10 keV energy range. The point-spread function (PSF) of the mirror modules has a FWHM of 6′–15′ depending on energy and is fully oversampled by the CCD pixel size in each instrument.
2.2. Basic Analysis

We analyzed data produced by the standard processing (SAS ver. 20020507...1701). The photon event lists were initially filtered for periods of high background, typically flare events corresponding to enhanced solar wind activity. To identify these flares, an iterative clipping method was used to generate the acceptable time intervals using the following method. We first produced a light curve histogram in 100 s steps for the whole instrument and calculated the mean. Intervals with an enhanced count rate $>3 \sigma$ above the mean were discarded and a new light curve was generated. This process was repeated until all points above the converging threshold were removed. The good time intervals thus generated were used to filter the revised event file. A total of $\sim 343$ ks of good exposure time was acquired from the collected data set; the net exposure times for each instrument are listed in Table 1. Finally, in creating spectra and images, we used the standard SAS screening flags and selected only CCD photons from the eastern "lobe" region, using a circle of radius $r < 0.5$.

2.3. Spatial Analysis

To search for evidence of a faint supernova remnant surrounding the pulsar, we generated exposure-corrected, narrowband images including data from all three instruments in order to obtain the deepest possible image. Figure 1 compares the image of 3C 58 in three energy bands to highlight the three spatial components that are found to make up the composite morphology: a shell-like nebula (0.5–1 keV), the pulsar wind nebula (PWN; 2.0–3.0 keV), and the point-like pulsar emission (7.0–8.0 keV).

To investigate further the nature of this shell-like emission we generated spectra from concentric annuli $30''$ wide to search for radial variations. These annuli were centered on the location of the pulsar, the presumed origin of the wind and likely center of any SNR expansion. To estimate the background in each annulus, we collected photons from within a region with $\sim 3.5'' < r < 4''$. Although the background is somewhat distant from the inner source regions, the high surface brightness of the source makes background subtraction less important there. We also extracted photons from the eastern "lobe" region, using a circle of radius $r < 0.5$.

Table 1

| ObsID       | Date (UT)       | Pointing (J2000.0) | Exposure (ks) |
|-------------|-----------------|--------------------|--------------|
| 153752201   | 2002 Sep 11, 04:29:35 | 2 4 43.6 +64 51 13.2 | 36777 15579 |
| 153751801   | 2002 Sep 11, 13:09:58 | 2 5 03.0 +64 47 38.6 | 39561 16328 |
| 153752501   | 2002 Sep 11, 20:03:41 | 2 5 23.4 +64 43 52.3 | 35195 14721 |
| 153752401   | 2002 Sep 12, 03:20:44 | 2 5 38.0 +64 49 40.0 | 26184 12568 |
| 153752101   | 2002 Sep 12, 04:22:11 | 2 5 18.9 +64 53 23.7 | 17363 3022 |
| 153751701   | 2002 Sep 13, 10:57:39 | 2 5 13.1 +64 51 41.8 | 13515 6042 |
| 153751801   | 2002 Sep 13, 17:51:22 | 2 5 52.6 +64 55 27.7 | 84831 21038 |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. All observations were obtained in pointed imaging mode with the thin transmission window in the focal plane; the EPIC MOS and pn data were collected with the Prime Full Window and Prime Large Window submodes, respectively.

A EPIC exposure times are after filtering; the EPIC MOS exposure times are for the sum of the two MOS cameras.
75" centered at coordinates R.A. = 02h06m14.6s and decl. = 64°49′31″; the background for this region was determined from a pair of apertures straddling the source region to the north and south.

2.4. Spectral Analysis

Spectra from each observation were extracted from each annular region using standard channel binning for each instrument, and a set of response matrices were generated for each ring using the standard prescription for diffuse emission. The spectra and response matrices were then summed over all observations for each instrument following the method used in ADDASCASPEC. The two sets of MOS spectra were then combined. Finally, all spectra were grouped into bins containing a minimum of 400 counts and fitted using the XSPEC spectral fitting package.

To fit the summed spectra in each annulus we used the following procedure. In all cases, the EPIC pn and EPIC MOS spectra were fitted simultaneously, with the model normalizations allowed to be independent to account for remaining flux calibration differences (±10%) between the two instruments (Saxton et al. 2003).

TABLE 2

Spectral Fits and Fluxes

| MODEL PARAMETER | 0.0−0.5 | 0.5−1.0 | 1.0−1.5 | 1.5−2.0 | 2.0−2.5 | 2.5−3.0 | 3.0−3.5 |
|-----------------|---------|---------|---------|---------|---------|---------|---------|
| N$_H$ (10$^{21}$ cm$^{-2}$) | 4.16 (4.09−4.24) | 4.16 (fixed) | 4.16 (fixed) | 4.16 (fixed) | 4.16 (fixed) | 4.16 (fixed) | 4.16 (fixed) |
| $\Gamma$ (spectral index) | 2.02 (2.01−2.04) | 2.29 (2.27−2.31) | 2.45 (2.43−2.48) | 2.55 (2.5−2.59) | 2.73 (2.67−2.78) | 2.81 (2.70−2.92) | 2.93 (2.75−3.12) |
| PL flux$^a$ pn (×10$^{-13}$) | 34.3 | 29.2 | 20.6 | 15.0 | 8.40 | 3.86 | 2.05 |
| PL flux$^a$ MOS (×10$^{-13}$) | 41.4 | 31.5 | 23.8 | 16.7 | 9.60 | 4.40 | 2.48 |
| $\chi^2$(dof) | 404.01 (442) | 207.01 (251) | 138.71 (196) | 129.18 (152) | 80.18 (101) | 36.98 (66) | 39.66 (52) |
| kT (keV) | 0.24 (fixed) | 0.24 (0.20−0.29) | 0.22 (0.20−0.24) | 0.22 (0.21−0.23) | 0.23 (0.22−0.23) | 0.23 (0.22−0.24) | 0.24 (0.21−0.28) |
| Ne (Ne/Ne$_{\odot}$) | 3.0 (fixed) | 5.5 (3.0−9.4) | 4.3 (3.6−8.4) | 3.1 (2.7−3.4) | 3.0 (2.8−3.3) | 3.6 (3.2−4.0) | 3.1 (2.2−4.4) |
| kT flux$^a$ pn (×10$^{-13}$) | ... | 0.27 | 0.63 | 1.16 | 1.39 | 0.96 | 0.26 |
| kT flux$^a$ MOS (×10$^{-13}$) | ... | 0.18 | 0.57 | 1.16 | 1.63 | 1.05 | 0.26 |
| $\chi^2$(dof) | 399.37 (443) | 373.58 (414) | 294.33 (365) | 345.91 (319) | 324.62 (252) | 140.76 (164) | 117.61 (125) |
| Total flux$^a$ pn (×10$^{-13}$) | 34.3 | 28.2 | 21.2 | 16.2 | 9.76 | 4.79 | 2.34 |
| Total flux$^a$ MOS (×10$^{-13}$) | 41.4 | 32.0 | 24.1 | 17.8 | 11.2 | 5.40 | 2.62 |

Note—Uncertainties are 90% confidence for two interesting parameters.

$^a$ Absorbed flux in the 0.5−10 keV band in units of (ergs cm$^{-2}$ s$^{-1}$).
The spectra were initially fitted in the 1.5–8.0 keV energy band with a power-law model for the nonthermal emission from the PWN. This model included the effects of interstellar absorption, although this is not an important component in the fitted band. The best-fit values for the power-law index and flux are recorded in Table 2. As illustrated in Figure 3, the spectrum above 1.2 keV is well characterized by a power-law model. However, at the lower energies, we require additional emission components for the larger annuli. We account for this excess by adding in a Raymond-Smith thermal plasma emission component to the model and extending the fitting range to 0.5–8.0 keV. In fitting this new model, the power-law indices were fixed to the values derived at high energies. As shown in the third panel of Figure 3, however, a strong line feature at $0.9 \text{ keV}$ remained unmodeled. This emission line corresponds to the He-like Ne $\alpha$ transition and requires an over-abundance $3 \times (\text{Ne}/\text{Ne}_0)$ in the Raymond-Smith plasma model throughout the nebula.

The column density, $N_{\text{H}}$, used to fit each spectrum was fixed to the value derived from the central annulus, the region with the most counts and in which the nonthermal emission strongly dominates over any thermal emission. In all cases, the final spectral fits produce an acceptable fit statistic, with the exception of the region between $r = 2''$ and $2.5''$, and perhaps the next interior one. This can be attributed to unmodeled structure below 0.8 keV, likely additional weak thermal line emission that we lack the sensitivity to model with the current data. Table 2 gives the best-fit values for the temperature and flux in each annulus after fixing the $\Gamma$ and $N_{\text{H}}$, while Figure 4 demonstrates the dramatic change in the thermal contribution as a function of radius and the high quality of the fits in the composite model.

The overall profile of the remnant is asymmetrical, with a lobe extending to the east. In order to determine whether this emission is powered strictly by an asymmetric relativistic wind from the pulsar (cf. Vela, Helfand et al. 2001; B1509–58, Gaensler et al. 2002) or represents the breakout of the hot gas into a region of low surrounding density, as is seen in some shell-type remnants, we analyzed the spectrum of the emission extracted from the lobe region defined above. Figure 5 displays the spectrum along with residuals from a power-law fit, which fixed the column density at the value used above for the remnant as a whole.

The spectra were initially fitted in the 1.5–8.0 keV energy band with a power-law model for the nonthermal emission from the PWN. This model included the effects of interstellar absorption, although this is not an important component in the fitted band. The best-fit values for the power-law index and flux are recorded in Table 2. As illustrated in Figure 3, the spectrum above 1.2 keV is well characterized by a power-law model. However, at the lower energies, we require additional emission components for the larger annuli. We account for this excess by adding in a Raymond-Smith thermal plasma emission component to the model and extending the fitting range to 0.5–8.0 keV. In fitting this new model, the power-law indices were fixed to the values derived at high energies. As shown in the third panel of Figure 3, however, a strong line feature at $0.9 \text{ keV}$ remained unmodeled. This emission line corresponds to the He-like Ne $\alpha$ transition and requires an over-abundance $3 \times (\text{Ne}/\text{Ne}_0)$ in the Raymond-Smith plasma model throughout the nebula.

The column density, $N_{\text{H}}$, used to fit each spectrum was fixed to the value derived from the central annulus, the region with the most counts and in which the nonthermal emission strongly dominates over any thermal emission. In all cases, the final spectral fits produce an acceptable fit statistic, with the exception of the region between $r = 2''$ and $2.5''$, and perhaps the next interior one. This can be attributed to unmodeled structure below 0.8 keV, likely additional weak thermal line emission that we lack the sensitivity to model with the current data. Table 2 gives the best-fit values for the temperature and flux in each annulus after fixing the $\Gamma$ and $N_{\text{H}}$, while Figure 4 demonstrates the dramatic change in the thermal contribution as a function of radius and the high quality of the fits in the composite model.

The overall profile of the remnant is asymmetrical, with a lobe extending to the east. In order to determine whether this emission is powered strictly by an asymmetric relativistic wind from the pulsar (cf. Vela, Helfand et al. 2001; B1509–58, Gaensler et al. 2002) or represents the breakout of the hot gas into a region of low surrounding density, as is seen in some shell-type remnants, we analyzed the spectrum of the emission extracted from the lobe region defined above. Figure 5 displays the spectrum along with residuals from a power-law fit, which fixed the column density at the value used above for the remnant as a whole.

The overall profile of the remnant is asymmetrical, with a lobe extending to the east. In order to determine whether this emission is powered strictly by an asymmetric relativistic wind from the pulsar (cf. Vela, Helfand et al. 2001; B1509–58, Gaensler et al. 2002) or represents the breakout of the hot gas into a region of low surrounding density, as is seen in some shell-type remnants, we analyzed the spectrum of the emission extracted from the lobe region defined above. Figure 5 displays the spectrum along with residuals from a power-law fit, which fixed the column density at the value used above for the remnant as a whole.

The overall profile of the remnant is asymmetrical, with a lobe extending to the east. In order to determine whether this emission is powered strictly by an asymmetric relativistic wind from the pulsar (cf. Vela, Helfand et al. 2001; B1509–58, Gaensler et al. 2002) or represents the breakout of the hot gas into a region of low surrounding density, as is seen in some shell-type remnants, we analyzed the spectrum of the emission extracted from the lobe region defined above. Figure 5 displays the spectrum along with residuals from a power-law fit, which fixed the column density at the value used above for the remnant as a whole.

The overall profile of the remnant is asymmetrical, with a lobe extending to the east. In order to determine whether this emission is powered strictly by an asymmetric relativistic wind from the pulsar (cf. Vela, Helfand et al. 2001; B1509–58, Gaensler et al. 2002) or represents the breakout of the hot gas into a region of low surrounding density, as is seen in some shell-type remnants, we analyzed the spectrum of the emission extracted from the lobe region defined above. Figure 5 displays the spectrum along with residuals from a power-law fit, which fixed the column density at the value used above for the remnant as a whole.
The spectrum is well characterized by a steep power law with index $\Gamma = 2.88 \pm 0.06$ with no hint of any thermal emission at low energies. The spectral index is the steepest value we measured, consistent with its location farthest from the pulsar (see Fig. 6).

3. DISCUSSION

In Figure 6, we illustrate the relative contributions of the thermal and nonthermal components as a function of radius. The thermal shell is clearly present. Note, however, that this thermal emission represents less than 4% of the observed (absorbed) flux of the remnant in the 0.5–10.0 keV band, explaining why it has proven so elusive to date. Figure 7 displays the radial dependence of the shell temperature and neon abundance; both are flat. In contrast, the power-law spectral index $\Gamma$ monotonically increases from $\Gamma = 1.9$ at the remnant center to $\Gamma = 2.8$ at the edge (and $\Gamma = 2.9$ in the eastern lobe). This latter result is generally consistent with earlier work (Torii et al. 2000; Slane et al. 2002), although owing to the much larger number of photons collected and the spectral-spatial decomposition we have performed, the measurements extend to a greater radius and differ in detail, remaining flat between 2'2 and 3'2.

The widths of the annuli provide largely independent measurements of the spectrum at each radius given the size of the PSF. Some contamination is present from the inner, brighter rings to the outer ones, however. Since the dominant power law is flatter than 2.5 in the central 0'5 circle, the power-law spectral index falls from 2.02 to 2.00, while in the first four annuli beyond this, the indices change as follows: 2.29 becomes 2.38, 2.45 becomes 2.50, 2.55 becomes 2.58, and 2.73 becomes 2.78. Thus, the rise in spectral slope is slightly steeper than shown in Figure 7. PSF contamination effects are negligible for the thermal component since the count rate is so low.

The parameters we derive for the shell are in excellent agreement with those inferred in the early work of Bocchino et al. (2001) and with those found from a portion of the shell in the deep Chandra observation of 3C 58 (Slane et al. 2004): the temperature and neon abundance are identical at $kT = 0.23$ keV and 3.2 solar, respectively. While these previous authors have cited the neon overabundance as evidence that we are seeing emission from the ejecta, a growing body of work (Cunha et al. 2006 and references therein) suggests that the solar abundance of neon has been systematically underestimated by a factor of 2. In that our fits do not require the statistically marginal enhancement of a factor of 2 in the Mg abundance reported by Slane et al. (2004); we argue that the provenance of the thermal emission remains an open question.

The total observed X-ray luminosity we derive for the shell component is $5.9 \times 10^{32} d_{12}^{2} \text{ergs s}^{-1}$, within the range found in Bocchino et al. (2001). This is significantly below the upper limit derived by Seward et al. (2006) for the missing Crab Nebula shell. The total mass is $\sim 0.77 M_{\odot}$ (for a mean molecular weight of 0.6, which may not be appropriate if the bulk of the radiating material is ejecta).

Evidence has been accumulating for some time that, despite the apparently robust conclusions drawn from the historical records that 3C 58 is coincident with SN 1181 (Stephenson & Green 1999), the remnant properties are inconsistent with such a young age. Bietenholz (2006) provides a comprehensive summary of the arguments against an association, as well as a list of alternative scenarios. Most of the evidence suggests a remnant age of $\sim 3000–5000$ yr (e.g., Chevalier 2005). Our spatially resolved image of the shell adds further to the case for an age $>820$ yr.

Using the X-ray-emitting mass we have derived and the analytic models of PWN evolution from Chevalier (2005) we can...
set limits on the apparent age of the remnant. From equation (27) of Chevalier (2005), we can combine the observed supernova remnant radius of \(2.8d_{3.2}\) pc and the pulsar timing-derived parameter \(\dot{E} = 2.7 \times 10^{37}\) erg s\(^{-1}\) to obtain the age \(t_3\) in units of 1000 yr,

\[
t_3 \approx 1.8M_{\odot}^{0.4}d_{51}^{0.2},
\]

where \(M_{\odot}\) is the ejected mass in units of solar mass \(M_{\odot}\). If we make the extreme assumption that all of the observed 0.77 \(M_{\odot}\) of X-ray-emitting gas is ejecta, and that it represents some fraction \(<1\) of the total ejected mass of the supernova, we find \(t_3 \approx 1.62E_{51}^{0.2}\). Thus, the pulsar must be at least twice the age of SN 1181 for reasonable explosion energies and, for a more plausible ejected mass of \(~5 M_{\odot}\), the age is 3400 yr. Alternatively, if we assume all of the observed gas has been swept up by the expanding PWN, from Chevalier’s (2005) equation (28), we find \(t = 5100\) yr (cf. the pulsar’s characteristic age of 5390 yr).

The pulsar’s location with respect to the circular shell of thermal X-ray emission provides a potential test that could resolve the age controversy. The location of the pulsar is marked with a crosshair in Figure 8 (right panel). It is apparent that this is not the center of the shell; a circle best matching the observed thermal emission is centered at \(2h5m33s, 63\deg 49'50''\) (J2000.0), with an uncertainty of 5'' in both coordinates. This lies offset by \(27''\) west (and slightly north) of the pulsar’s location. For an age of 821 yr, a distance of 3.2 kpc, and spherical expansion (an assumption supported by the fact we see no thermal emission in the eastern elongation of the remnant), this requires a two-dimensional pulsar velocity of 500\(d_{3.2}\) km s\(^{-1}\). While not impossible for a young neutron star, it is worth noting that if the object has the same transverse velocity as the Crab pulsar, the remnant age would be 3750\(d_{3.2}\) yr, consistent with other estimates. We further note that the implied trajectory for the pulsar aligns to within a few degrees of the long axis of the nebula, behavior commonly seen among PWNe. If Chandra survives for another decade, it will be possible to resolve this issue directly, as the implied proper motion of 0.5'' for the high-velocity scenario will be directly measurable.

This research is supported by NASA LTSA grant NAG 5-8063 to E. V. G. and by grant SAO GO3-4026B to D. J. H. This research has also made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA’s Goddard Space Flight Center.

REFERENCES

Bietenholz, M. F. 2006, ApJ, 645, 1180
Bocchino, F., Warwick, R. S., Marty, P., Lumb, D., Becker, W., & Pigot, C. 2001, A&A, 369, 1078
Chevalier, R. A. 2005, ApJ, 619, 839
Cunha, K., Hubeny, I., & Lanz, T. 2006, ApJ, 647, L143
Fesen, R. A. 1983, ApJ, 270, L53
Gaensler, B. M., Arons, J., Kaspi, V. M., Pivovaroff, M. J., Kawai, N., & Tamura, K. 2002, ApJ, 569, 878
Gottelf, D. J., Gotthelf, E. V., & Halpern, J. P. 2001, ApJ, 556, 380
Jansen, F., et al. 2001, A&A, 365, L1
Janssen, J. J. L., et al. 2004, A&A, 420, 853
Lumb, D. H., et al. 2004, A&A, 420, 853

Reynolds, S. P., & Aller, H. D. 1985, AJ, 90, 2312
Saxton, R. D. 2003, Astron. Nachr., 324, 138
Seward, F. D., Gorenstein, P., & Smith, R. K. 2000, ApJ, 636, 873
Saxton, R. D. 2003, Astron. Nachr., 324, 138
Seward, F. D., Gorenstein, P., & Smith, R. K. 2000, ApJ, 636, 873
Slane, P., Helfand, D. J., van der Swaluw, E., & Murray, S. S. 2004, ApJ, 616, 403
Slane, P. O., Helfand, D. J., & Murray, S. S. 2002, ApJ, 571, L45
Stephenson, F. R., & Green, D. A. 1999, Astron. Geophys., 40, 27
Tori, K., Slane, P. O., Kinugasa, K., Hashimoto, K., & Tsunemi, H. 2000, PASI, 52, 875
Turner, M. J. L., Briel, U. G., Ferrando, P., Griffiths, R. G., & Villa, G. E. 2003, Proc. SPIE, 4851, 169

Fig. 8.—X-ray image of the pulsar wind nebula and the thermal shell in the supernova remnant 3C 58. These images are the mosaic of eight observations acquired with the XMM-Newton EPIC cameras. Left: The 1.0–2.0 keV exposure-corrected image with contours illustrates the morphology of the PWN and “lobe” regions. The image is scaled to enhance the fainter nebula emission with contours overlayed. Right: Same data but in the 0.5–1.0 keV energy band with the nonthermal contribution subtracted (see text). The intensity is scaled linearly and the contours are equally spaced. The symmetric, filled shell-like structure is 

\[
\text{GOTTHELF, HELFAND, & NEWBURGH}272
\]