PSR 1509-58 and its Plerionic Environment

C. Greiveldinger [1], S. Caucino [2], S. Massaglia [2], H. Ögelman [1], and E. Trussoni [2]

ABSTRACT

ROSAT Position Sensitive Proportional Counter observations of PSR 1509-58 in the supernova remnant MSH 15-52 reveal the presence of a compact nebula around the pulsar with an average radius of $\sim 50''$ at energies between 0.7 and 1.5 keV. The radius decreases to $\sim 30''$ between 1.5 and 1.8 keV, and at higher energies it appears to be absent. Spectral analysis of the compact nebula reveals that its emission is softer than the emission from the pulsar. The pulsar has a pulsed fraction that is relatively constant over the ROSAT band with an average value of 56$\pm$10%. The pulse shape remains relatively stable over the ROSAT range with exceptions at the highest and lowest energies where the photon statistics are poorest. The arrival phase of the X-ray pulse is constant over the ROSAT energy range, but a comparison to radio, higher energy X-ray and gamma-ray observations shows a trend of greater separation from the radio peak in pulse arrival phase at higher energies. Confining the power-law photon index for the pulsed spectrum to the values allowed from spectral fits to EXOSAT, GINGA, and SIGMA data (-1.4 to -0.3), we determine that $N_H \approx 9.5 \times 10^{21}$ cm^{-2} and the flux in the 0.1-2.4 keV energy range $\sim 6 \times 10^{-12}$ ergs cm^{-2} s^{-1}.

1. Introduction

PSR 1509-58 is one of the few pulsars that has been found within a supernova remnant. It was first discovered in the remnant MSH 15-52 in X-rays with the EINSTEIN observatory (Seward & Harnden 1982). Soon afterwards the pulsar was detected in radio by Manchester, Tuohy, & D'Amico (1982). PSR 1509-58 has a period of 150 ms and a period derivative of $1.5 \times 10^{-12} ss^{-1}$, the fastest period derivative observed for a pulsar. This gives PSR 1509-58 the largest derived pulsar magnetic field (B=1.4$\times 10^{13}$ Gauss) and the second youngest spin-down age, $P/2\dot{P}$ $\sim$1600 years, Crab being the youngest. The X-ray emission of

[1]Department of Physics, University of Wisconsin–Madison, 1150 University Avenue, Madison, WI 53706, USA

[2]Osservatorio Astronomico di Torino, Strada dell'Osservatorio 20, I-10025 Pino Torinese, Italy

supernova remnant MSH 15-52 around the pulsar is also similar to that of the Crab Nebula and its pulsar, in the sense that it is plerionic (centrally-filled) and appears to be pulsar-driven, but the shape is significantly different (Fig. 1). There is also another compact, but resolved, X-ray source within the remnant MSH 15-52 to the northwest of the pulsar that is coincident with the Hα emitting region RCW 89 (Rodgers, Campbell, & Whiteoak 1960), which will be referred to as the northern source from here on. The pulsar and the northern source are connected by a bridge of X-ray emission which constitutes the majority of the supernova remnant radiation. The origin of the northern source is still unknown, but possible explanations that have been proposed by Seward et al. (1983) include: the supernova occurring close to the northern source, supernova energy being preferentially directed toward the northern source, and energy from the pulsar being channeled in the direction of the northern source, which is reminiscent of the situation in the Vela supernova remnant where there is an X-ray 'jet' that extends from the pulsar to the southwest (Markwardt & Ögelman 1995).

The presence of a radio shell around the X-ray plerion qualifies MSH 15-52 as a composite remnant. From the size of this radio shell, the remnant was initially believed to be roughly 10^4 years old (Clark & Caswell 1977), while the dynamical age of the pulsar is 1600 years, as mentioned above. This age discrepancy can be resolved if the supernova event that caused the remnant was extremely energetic and occurred in a rarefied medium (Seward et al. 1983). Thorsett (1992) has identified the supernova event as being a 'guest star' as reported in Chinese records in 185 AD, lending credence to the thought that the remnant is indeed younger than preliminary estimates stated. Recently, however, Chin & Huang (1994) have reported that the guest star may in fact have been a comet, in which case the ages of the remnant and pulsar are still problematic.

Because evidence for the presence of compact X-ray nebulae has been found for pulsars in supernova remnants, in particular for the pulsar in the Vela supernova remnant (Harnden et al. 1985, Ögelman, Finley, & Zimmermann 1993) and PSR 1951+32 in the remnant CTB 80 (Safi-Harb et al. 1995), we searched for evidence of a similar feature around PSR 1509-58. In the relatively young Vela pulsar ($\tau \sim 10^4$ years), where the point source X-ray emission appears to be thermal radiation from the neutron star's surface, the compact nebula exhibits emission that is harder than that seen from the pulsar. In the older pulsar PSR 1951+32 ($\tau \sim 10^5$ years) the reverse appears to be true; the pulsar emission is harder than that of its surrounding compact nebula. The Crab pulsar is also surrounded by an X-ray emitting torus (Brinkmann et al. 1985), but such structures could not be resolved around PSR 1509-58 with the PSPC.

In this paper we present the details of the ROSAT observations and the search for the compact nebula around the pulsar. Then we discuss our timing and pulse shape analysis, and finally we mention spectra of the pulsar and the compact nebula. The remnant in its entirety is discussed in Trussoni et al. (1995).

2. Observations

ROSAT observations of MSH 15-52 were taken with the Position Sensitive Proportional Counter (PSPC) from 1991 February 22–March 8 and again from 1992 February 25–27 for a total of 9135 seconds. Details regarding the satellite, X-ray mirrors and detectors can be found in Trümper (1983) and Pfeffermann et al. (1986). The satellite was pointed at the pulsar, and the 100$''$ region around and including the pulsar yielded a count rate of $\sim$0.4 c s^{-1} including the background rate. The data were checked for software errors in the timing and none were found. The large distance to the pulsar and subsequent column density result in large absorption of lower energy photons, and the counts are very low at energies below 0.7 keV (Fig. 2), and it can be concluded that the lower energy photons are a product of the low energy tail of the detector response to higher energy photons. The northern source is resolved as a region of compact, but extended X-ray emission in the PSPC image. Data processing and analysis were performed using Midas/Exsas software package (Zimmermann et al. 1993).

3. Search for a Compact Nebula around the Pulsar

As was mentioned previously PSR 1509-58 is embedded in an X-ray emitting plerion type supernova remnant. We looked further for evidence of a compact nebula around the pulsar. The region studied is a 100$''$ radius ring centered on the pulsar's position. This size was chosen so that remnant emission would be fairly constant in the studied region which allowed us to neglect the morphology of the remnant. At the lower ROSAT energies (0.7-1.8 keV) the radial count density profile cannot be fit by a point source and a flat background that would be due to the supernova remnant. The clearest example of this excess emission occurs at energies 1.3-1.5 keV and is shown in Figure 3. There is excess emission at 20$''$ to 60$''$ from the pulsar. We attempted to model the observed radial count density profile with three components: a point source, a compact nebula, and a flat background from the supernova remnant. We did this by combining the point response function of the ROSAT PSPC with flat background emission, and a model for compact nebula emission. Because the point response function of the ROSAT PSPC varies with energy (Hasinger et al. 1992), this model was fit to the observed radial profile in six energy bands by varying the following parameters: $N_s(E)$, the counts from the point source; $N_{bg}(E)$, a flat background emission which will be dominated by the emission from the SNR; $N_n(E)$, the number of photons in the compact nebula, and $r_n(E)$, the radius that encircles half the nebular photons.

The goodness of fit for a given set of parameters was determined by the χ^2 statistic. From the best fit in each energy bin the fraction of the emission due to the pulsar was determined by integrating the point spread function out to $100''$ (Table 1), with errors assigned at the 90% confidence level from the range of acceptable models through the method outlined by Lampton, Margon, & Bowyer (1976). Also included in Table 1 are the total number of photons from the pulsar for each energy bin. The fits provide χ^2 values that are better than those in which the emission is represented by a point source and a flat background, but only at energies less than 1.8 keV are the differences significant enough ($\geq 2\sigma$) to claim the presence of a compact nebula. The highest energy bin also shows a 2σ improvement, but the derived radius of the compact nebula was considerably smaller than the angular resolution of the PSPC, and the PSF at the highest energies is not well documented (Hasinger et al. 1992). Therefore this higher energy fit is disregarded, and we conclude that four of the six energy bins show evidence of a compact nebula surrounding PSR 1509-58. The average radius (r_n) of the compact nebula for 0.7 keV $<$ E $<$ 1.5 keV is $46'' \pm 5''$ and between 1.5 and 1.8 keV the radius drops to $\sim 30''$, the angular resolution of the PSPC. It is important to realize that we do not convolve the compact nebula model with the PSPC point response function, so the actual radius of the nebula could be as much as 35% smaller than indicated here.

4. Pulsed Fraction and Pulse Phase Energy Dependence

The arrival times of the photons were corrected to the solar system barycenter using the JPL DE200 ephemeris and the J2000 coordinates of $\alpha = 15^h 13^m 55\overset{s}{.}66$ and $\delta = -59°8'\,9\overset{''}{.}09$. The stability of the rotation rate of PSR 1509-58 and the accuracy of the radio ephemeris (Johnston et al. 1992) allowed us to directly phase-relate each X-ray photon to the radio pulse without utilizing a parameter search. Figure 4 shows the data folded at the pulsar ephemeris listed in Table 2. The pulsed fraction and phase are determined through the Z_1^2 statistic (Buccheri et al. 1983):

$$Z_1^2 = (2/N)\left[\left(\sum_{i=1}^{N} cos 2\pi\phi_i\right)^2 + \left(\sum_{i=1}^{N} sin 2\pi\phi_i\right)^2\right],$$

where N is the total number of events and ϕ_i is the residual phase of the ith event ($\phi_i = f_0 t + \frac{1}{2}\dot{f}t^2 + \frac{1}{6}\ddot{f}t^3$). Since the Z_1^2 statistic is distributed like χ^2 with 2 degrees of freedom, the pulsed fraction (defined as (mean-minimum)/mean) for the fundamental mode of sinusoidally varying emission will be given by p.f.=$\sqrt{\frac{2(Z_1^2-2)}{N}}$. Since the fundamental mode provides the most power in the Z_1^2 test at each energy and the pulse shape remains similar over the energy range, it is reasonable to characterize variations in the pulse shape with the fundamental mode alone. Table 1 shows the fraction of the emission in the 100″ region that is pulsed in each of the energy bins, indicating the fraction of combined point source and nebular emission that is pulsed. The point source pulsed fraction is calculated by taking the ratio of the pulsed emission fraction (as determined by the Z_1^2 test) to the modeled point source emission fraction (Figure 5). The pulsed fraction does not exhibit significant energy variation at the lower energies, but does show a decrease at higher energies. The energy-averaged pulsed fraction of the pulsar is determined to be $56 \pm 10\%$, less than the lower limit of 80% determined by Seward & Harnden with EINSTEIN (1982).

The relative phase of the arrival of the fundamental mode was determined for each energy bin by using

$$\Phi = tan^{-1}\left(\frac{\sum_{i=1}^{N} sin2\pi\phi_i}{\sum_{i=1}^{N} cos2\pi\phi_i}\right).$$

This phase determination is valid for the first harmonic and does not necessarily coincide with the pulse peak. This technique has been used to alleviate errors in estimating phases of pulse peaks when relatively low numbers of photons are being considered. Figure 6 shows the phase of the fundamental mode as a function of energy in the ROSAT bandpass. Over this range the phase remains remarkably constant in contrast to some of the cooling neutron stars that have been observed by ROSAT like PSR 0656+14 (Finley et al. 1992), PSR 1055-52 (Ögelman & Finley 1993) and Geminga (Halpern & Ruderman 1993). Even though the pulse phase is constant in this energy range, when compared to other energy ranges, some differences are evident. The peak of the ROSAT pulse lags the radio peak by 0.13±0.05, and at higher energies (2-11 keV, Kawai et al. 1991 and 20-480 keV, Ulmer et al. 1993) this lag increases to ~ 0.32. Figure 7 shows a plot of the difference in pulse arrival phase between higher energies and radio. This behavior is also different from that seen in the Crab pulsar where pulsations at all energies arrive at the same time as the radio pulse (e.g. Agrinier et al. 1989).

5. Pulsed Spectrum

Based on the determination by Seward & Harnden (1982) that PSR 1509-58 was $> 80\%$ pulsed, spectra of only the pulsed X-ray component have been used to describe the spectrum of the neutron star (Seward, Harnden, & Elsner 1985; Trussoni et al. 1990). We follow this convention to see how the ROSAT spectrum compares to previously determined spectra. The off-pulse component was used as the background for the on-pulse source. Unfortunately the high neutral hydrogen column density ($N_H \approx 9 \times 10^{21}$ cm^{-2}) in the direction of PSR 1509-58 causes large absorption in the ROSAT bandpass and makes it difficult to free fit a model to the extracted spectrum. With the EXOSAT data Trussoni et al. (1990) were able to determine the power-law index, but they could not constrain the column density along the line of sight. Working under the assumption that the power-law fit to the EXOSAT pulsed spectrum ($\frac{dN}{dE} \propto E^{\alpha}$, Trussoni et al. 1990) continues into the ROSAT range we are able to constrain the column density and flux in the range 0.1-2.4 keV (Table 3). The best fit to the ROSAT data yields a reduced χ^2 of 0.49 for 7 degrees of freedom. The results for this fit are (using the EXOSAT photon index α=-1.1): N_H=$8.7^{+9.8}_{-5.2} \times 10^{21}$ cm^{-2} and flux (0.1-2.4 keV)=$4.7^{+6.5}_{-2.7} \times 10^{-12}$ergs cm^{-2} s^{-1}, which, at a distance of 4.2 kpc, translates to a luminosity of $9.9^{+13.7}_{-5.7} \times 10^{33}$ ergs s^{-1}. Since the large column density yields a significant optical depth at energies below 1 keV, the flux determinations are model-dependent extrapolations from the data at higher energies.

Two other high energy X-ray satellites observed PSR 1509-58 as well. The SIGMA telescope determined a spectrum that is in agreement with the EXOSAT spectrum (Laurent et al. 1994), but the GINGA results (Kawai, Okayasu, & Sekimoto 1992) yield a flux in the range 0.1-2.4 keV that is $\sim$10 times greater than that predicted from the EXOSAT or SIGMA data. We performed another spectral fit where we allowed the power law index to vary between the values quoted for the fits for the three above satellites ($-1.4 \le \alpha \le -0.3$). This procedure gives N_H=$9.5^{+10.2}_{-7.5} \times 10^{21}$ cm^{-2} and flux (0.1-2.4 keV)=$6.0^{+9.1}_{-3.7} \times 10^{-12}$ergs cm^{-2} s^{-1} (Table 3). The best fit power-law index was -1.4, but no significance can be placed on this value from the ROSAT data because the χ^2 contours are not closed within this range of indices.

The best fit flux that is determined for the pulsed spectrum of the ROSAT data falls between the expected fluxes from the extrapolation of the best fit EXOSAT, SIGMA, and GINGA spectra. The GINGA extrapolation is $\sim$ 2 times larger than the best fit, while the other two predict a flux that is $\sim$ 3 times lower than determined. However, within the 3σ errors quoted for the flux both the EXOSAT and GINGA spectra are consistent with the ROSAT determination, while the flux from the SIGMA spectrum lies just outside the 3σ contours. The column density determined is consistent with what had been determined previously with EXOSAT and GINGA, and the SIGMA spectrum is not affected by interstellar absorption.

6. Spectra of the Point Source and Compact Nebula

We also tried to determine the spectra of the pulsar and compact nebula through our radial profile modeling results. The spectra are shown in Figure 1, and Table 3 contains the spectral fit parameters. By restricting the column density to the best fit value determined above from the pulsed spectrum (9.5×10^{21} cm^{-2}), we are able to determine that at the 3σ level, the power-law fit to the point source spectrum yields a photon index $\alpha \geq -1.4$ and a flux $9.3^{+5.1}_{-1.3} \times 10^{-12}$ergs cm^{-2} s^{-1}. The power-law fit to the compact nebula spectrum gives $\alpha \leq -2.0$, and flux $\geq 9.6 \times 10^{-12}$ergs cm^{-2} s^{-1}. At a distance of 4.2 kpc these fluxes correspond to luminosities of $2.0^{+1.1}_{-0.3} \times 10^{34}$ ergs s^{-1} and $\geq 2.0 \times 10^{34}$ ergs s^{-1} for the pulsar and the compact nebula, respectively. Combined, they account for only a small fraction ($\geq 0.2\%$) of the 1.8×10^{37} ergs s^{-1} available from the pulsar spin-down luminosity.

7. Discussion

In summary, we have found a compact nebula encircling the pulsar PSR 1509-58, and the X-ray emission from the nebula is softer than that from the pulsar. The pulsed fraction for the pulsar has been determined to be relatively stable over the ROSAT passband with an average value of $56 \pm 10\%$. The arrival of the peak of emission in the ROSAT band is also constant, but it lags the radio pulse peak by a phase of $\sim$0.13. This lag gets larger as higher energy X-rays and γ-rays are studied.

Compact nebulae have been discovered around pulsars with very disparate characteristics, and it is not known what determines the presence or the size of a compact nebula around a pulsar. The model of Rees & Gunn (1974) accurately describes the size of the X-ray torus around the Crab pulsar. In this model the size of the X-ray emitting region is limited by the radius at which the ram pressure of the pulsar's relativistic wind balances the pressure contained within the volume of the Crab nebula. The compact nebula around PSR 1509-58 also is in agreement with this model. Taking the radius of the supernova remnant to be $8'$ (the distance from the pulsar to the northern source), the model predicts the radius of the compact nebula to be $\sim70''$ (1.4 pc at a distance of 4.2 kpc). The measured radius of the nebula is $\sim50''$ (0.9 pc) which is comparable to what is expected. The model used here is very simplistic, and the assumptions used could account for the discrepancy in radii. For instance, the model assumes a spherical nebular cavity that has had particles uniformly injected into it at a steady rate over its lifetime, which does not appear to be the case at least for PSR 1509-58. Aschenbach & Brinkmann (1975) present a model in which the relativistic wind is confined to the pulsar's equatorial region, which should be considered for PSR 1509-58 once higher resolution images of the remnant are obtained. The size of the Crab X-ray torus is $\sim$0.1 pc, and the large difference in size between the Crab torus and the compact nebula of PSR 1509-58 is due to the fact that the Crab nebula is much smaller than the remnant MSH 15-52. Therefore the pressure built up in the volume of MSH 15-52 is less, and the relativistic wind can flow out to a larger radius before the ram pressure equals the nebular pressure.

Even though this model seems to provide a reasonable explanation for what is happening around the two young pulsars, the Crab pulsar and PSR 1509-58, it does not adequately describe all the compact nebulae that have been seen. The compact nebula around the Vela pulsar (Harnden et al. 1985) has a radius of $\sim$0.15 pc, but application of the Rees & Gunn model predicts a radius of $\sim$2 pc. This model may not be acceptable for the Vela pulsar because of the presence of an X-ray jet that appears to be originating from the pulsar (Markwardt & Ögelman 1995). If a large fraction of the Vela pulsar's relativistic wind is directed through the jet, then the assumption of a radial outflow is violated, and the Rees & Gunn model is not applicable. In this case it may be that the size of the X-ray jet determines the dimensions of any surrounding compact nebula. If the bridge of X-ray emission connecting PSR 1509-58 to the northern source is indeed a jet of material, then the applicability of the Rees & Gunn model to PSR 1509-58 will have to be reconsidered. A compact nebula has also been identified around PSR 1951+32 (Safi-Harb et al. 1995), but this pulsar appears to be traveling through its own supernova remnant shell, and the model for the Crab nebula would not be expected to work for such a case. Neither the Vela pulsar nor PSR 1951+32 seems to have a dominant effect on the morphology of its immediate surroundings (with the exception of the Vela pulsar's jet), and this would explain why the Rees & Gunn predictions would be in error. If the dominant pressure is provided by something other than the pulsar's luminosity, there would still be a shock where the relativistic wind's ram pressure would balance this external pressure. In the case of PSR 1951+32 this external pressure is the ram pressure of the interstellar medium, and using this a shock radius is calculated that is in agreement with the displacement of a radio hot spot from the pulsar (Safi-Harb et al. 1995).

Although our analysis seems to indicate that the pulsed fraction may be decreasing with energy, both Seward & Harnden (1982) and Laurent et al. (1994) show that the pulsed fraction is larger at higher energies. Seward & Harnden (1982) found that between 0.2 and 4 keV the pulsar is more than 80% pulsed, and Laurent et al. (1994) determined the pulsed fraction in the 40 to 300 keV energy range of SIGMA is 93$\pm$30%. These results are consistent with the observation that the size of the compact nebula appears to decrease with increasing energy. The fact that the point response function of the PSPC is poorly understood at high energies may account for the apparent trend in our data. Higher resolution observations of PSR 1509-58 would be helpful in confirming the presence of the compact nebula and discerning any features that may indicate a toroidal structure like that seen in the Crab nebula or a jet structure similar to the Vela pulsar.

8. Acknowledgments

We would like to thank W. Kluźniak, C. Markwardt, and S. Safi-Harb for helpful discussions and B. Aschenbach and W. Brinkmann for suggestions on the manuscript. This research was supported by NASA grant NAGW-2643.

Table 1.

Total counts and emission fractions as determined by modeling the compact nebula around the pulsar. The second column gives the number of photons from the pulsar in the given energy range. The third column indicates what fraction of the emission in the 100″ region around the pulsar is due to the point source. The fourth column is the fraction of the emission in the 100″ region that is pulsed, and the fifth column is the ratio of columns three and two, which gives the fraction of the point source emission which is pulsed.

Energy (keV)	Point Source Counts	Point Source Fraction	Pulsed Emission Fraction	Point Source Pulsed Fraction
0.70-0.97	75^{+18}_{-21}	$0.22^{+.04}_{-.06}$	0.15 ± 0.03	$0.68^{+.32}_{-.26}$
0.98-1.25	244^{+29}_{-34}	$0.29^{+.02}_{-.03}$	0.21 ± 0.01	$0.72^{+.13}_{-.07}$
1.26-1.53	366^{+31}_{-48}	$0.35^{+.04}_{-.02}$	0.19 ± 0.01	$0.54^{+.06}_{-.08}$
1.54-1.81	305^{+44}_{-35}	0.38 ± 0.03	0.26 ± 0.01	$0.68^{+.09}_{-.07}$
1.82-2.10	285^{+55}_{-35}	$0.66^{+.03}_{-.02}$	0.25 ± 0.02	$0.38^{+.04}_{-.05}$
2.11-2.40	77^{+36}_{-23}	$0.44^{+.16}_{-.11}$	0.06 ± 0.06	$0.14^{+.22}_{-.14}$

Table 2.
Pulsar Rotational Parameters

f = 6.6375697299830 Hz
$\dot{f}$ = -6.76954$\times10^{-11}$ Hz s^{-1}
$\ddot{f}$= 1.96 $\times$ 10^{-21} Hz s^{-2}
epoch (TDB) = 2448355.500000507

Table 3.

Parameters from power law fits to the ROSAT data. Model 1 is a fixed power-law index of α=-1.1, where $\frac{dN}{dE} \propto E^{\alpha}$. Model 2 allows the power-law index to vary between the ranges set by the GINGA and EXOSAT satellites (-1.4$\leq$ α $\leq$-1.0). The point source and compact nebula spectra are determined from the modeling of the compact nebula around the pulsar. N_H is in units of 10^{21}cm^{-2}, and flux is 10^{-12} ergs cm^{-2} s^{-1}.

Parameter	Pulsed Emission Model 1	Model 2	Point Source	Compact Nebula
N_H	$8.7^{+9.8}_{-5.2}$	$9.5^{+10.2}_{-5.6}$	9.5 (fixed)	9.5 (fixed)
Flux	$4.7^{+6.5}_{-2.7}$	$6.0^{+9.1}_{-3.7}$	$9.3^{+5.1}_{-1.3}$	≥ 9.6
Photon Index	-1.1 (fixed)	-1.4	≥ -1.4	≤ -2.0

REFERENCES

Agrinier, B. et al. 1989, Timing Neutron Stars, eds. H. Ögelman & E. P. J. van den Heuvel, Kluwer Academic Publishers, 343

Aschenbach, B., & Brinkmann, W. 1975, A&A, 41, 147

Brinkmann, W., Aschenbach, B., & Langmeier, A. 1985, Nature, 313, 662

Buccheri, R. et al. 1983, A&A, 128, 245

Chin, Y.-N., & Huang, Y.-L. 1994, Nature, 371, 398

Clark, D. H., & Caswell, J. L. 1977, MNRAS, 174, 267

Finley, J. P., Ögelman, H., & Kızıloğlu, Ü. 1992, ApJ, 394, L21

Halpern, J. P. & Ruderman, M. 1993, ApJ, 415, 286

Harnden, F. R., Jr., Grant, P. D., Seward, F. D., & Kahn, S. M. 1985, ApJ, 299, 828

Hasinger, G., Turner, T. J., George, I. M., & Boese, G. 1992, OGIP Calibration Memo CAL/ROS/92-001

Johnston, S., Kaspi, V., Manchester, R. N., & D'Amico, N. 1992, GRO/radio timing data base, Princeton University

Kawai, N., Okayasu, R., Brinkmann, W., Manchester, R., Lyne, A. G., & D'Amico, N. 1991, ApJ, 383, L65

Kawai, N., Okayasu, R., & Sekimoto Y. 1992, Proc. Workshop Compton Observatory, eds. M. Friedlander, N. Gehrels, and D. J. Macomb, AIP, 213

Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 177

Laurent, P. et al. 1994, A&A, 286, 838

Manchester, R. W., Tuohy, I. R., & D'Amico, N. 1982, ApJ, 262 L31

Markwardt, C., & Ögelman, H. 1995, Nature, 375, 40

Ögelman, H., & Finley, J. P. 1993, ApJ, 413, L31

Ögelman, H., Finley, J. P., & Zimmermann 1993, Nature, 361, 136

Pfeffermann, E. et al. 1986, SPIE, 733, 519

Rees, M. J., & Gunn, J. E. 1974, MNRAS, 167, 1

Rodgers, A., Campbell, C. T., & Whiteoak, J. B. 1968, MNRAS, 121, 103

Safi-Harb, S., Ögelman, H., & Finley, J. P. 1995, ApJ, 439, 722

Seward, F. D. & Harnden, F. R., Jr. 1982, ApJ, 256, l45

Seward, F. D., Harnden, F. R., Jr., & Elsner, R. F. 1985, Proc. Workshop The Crab Nebula and Related Supernova Remnants, eds. M. C. Kafatos, and R. B. C. Henry, Cambridge University Press, 165

Seward, F. D., Harnden, F. R., Jr., Murdin, P., & Clark, D. H. 1983, ApJ, 267, 698

Trümper, J. 1983, Adv. Spa. Res., 2, 241

Trussoni, E., Brinkmann, W., Ögelman, H., Hasinger, G., Aschenbach, B., & Ferrari, A. 1990, A&A, 234, 403

Trussoni, E., Massaglia, S., Caucino, S., Brinkmann, W., & Aschenbach, B. 1995, submitted to A&A

Ulmer, M. P., et al. 1993, ApJ, 417, 738

Zimmermann, H. U., Belloni, T., Izzo C., Kahabka P., & Schwenkter, O. 1993, in: EXSAS User's Guide, MPE Report 244

This preprint was prepared with the AAS LaTeX macros v3.0.

Fig. 1.— ROSAT X-ray contours of MSH 15-52 plotted over a grayscale image of the same data. The image was smoothed with a Gaussian of $2.5''$ radius, and the contour levels are at 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, and 3.0 counts per $2.5''$ square pixel. The pulsar is located at the center of the image, and the upper compact source is referred to as the northern source in the text. The line in the lower right corner of the image is one arcminute long. North is to the top of the figure, and west is to the right.

Fig. 2.— ROSAT count rate spectra of PSR 1509-58. The high column density along the line of sight to the pulsar absorbs the photons below channel 70. The spectra displayed are: (a) the pulsed spectrum, (b) the point source spectrum, and (c) the compact nebula spectrum. For (b) and (c) the spectra were only determined for channels greater than 70 (see text for details).

Fig. 3.— Radial count density profile of the $100''$ region centered on the pulsar for photons with energies between 1.3 and 1.5 keV. The large dashes represent the best fit using a point source (short dashes) and a flat background emission (dash-dot). Note that the model underestimates the number of photons at distances of $\sim 40''$ from the pulsar. The presence of a compact nebula can account for this excess.

Fig. 4.— ROSAT X-ray pulse shape with zero phase corresponding to the radio peak. A representative error bar is plotted at the peak of the X-ray pulse.

Fig. 5.— Pulsed fraction across the ROSAT energy range as determined by the Z_1^2 test.

Fig. 6.— X-ray pulse phase across the ROSAT energy range as determined by the Z_1^2 test. Zero phase corresponds to the arrival of the peak of the radio pulse.

Fig. 7.— Difference in phase between the radio pulse and higher energy pulses. The lowest energies plotted are from ROSAT, while the other two are from GINGA (Kawai et al. 1991) and GRO (Ulmer et al. 1993). Zero phase corresponds to the arrival of the peak of the radio pulse.