

THE X-RAY NEBULA AROUND PSR 1509-58

F. D. SEWARD AND F. R. HARNDEN, JR.
 Harvard-Smithsonian Center for Astrophysics

AND

A. SZYMKOWIAK AND J. SWANK
 Goddard Space Flight Center

Received 1983 September 23; accepted 1983 December 15

ABSTRACT

With the use of measured spectra and a model, volumes and luminosities are derived for several components of the supernova remnant MSH 15-52. The hard, featureless spectrum and spatial symmetry of the X-ray nebula surrounding the central pulsar strongly indicate synchrotron radiation as the source of emission. Power requirements are easily supplied by the pulsar. The observed surface brightness is only 2×10^{-5} that of the X-ray synchrotron emission around the Crab pulsar, and the X-ray luminosity is 10^{-2} that of the Crab. In spite of the great difference in luminosity and size, the two systems are probably similar in nature, with the high brightness and unique appearance of the Crab synchrotron nebula being due to the high energy output of the pulsar and the relatively small volume of the confining filaments.

Subject headings: nebulae: individual — nebulae: supernova remnants — pulsars — radiation mechanisms — X-rays: sources

I. INTRODUCTION

The recent discovery of an X-ray/radio pulsar within MSH 15-52 by Seward and Harnden (1982) and by Manchester, Tuohy, and D'Amico (1982) provides a link between the Crab Nebula and other supernova remnants (SNR). The Crab, with its fast pulsar and bright synchrotron nebula, has long been thought to be unique among SNRs, and without question, it is the brightest such system in our galaxy in the soft X-ray band (0.2–4 keV). Ninety-five percent of the soft X-ray luminosity comes from the synchrotron nebula which has the highest surface brightness of any diffuse X-ray source observed by the *Einstein X-Ray Observatory*, and it is primarily this bright synchrotron nebula that gives the Crab its unique character. Since this nebula is powered by spin-down of the pulsar, the existence or nonexistence of synchrotron nebulae has been used to infer the presence or absence of pulsars in other SNRs.

The pulsar and surrounding nebular emission within MSH 15-52 is the first clear-cut example of another Crab-like system, an X-ray/radio pulsar with associated synchrotron nebulosity. The nebula is clearly seen in X-rays and is probably not detectable at other wavelengths. In this paper we will argue on the basis of spectrum and morphology that the luminosity is indeed synchrotron emission powered by PSR 1509-58. We will use the *Einstein* data to derive

its shape, volume, and luminosity. Since there is apparently little confusion with thermal X-rays from the SNR shell, this can be done accurately. Because the Crab has an anomalously low expansion velocity and size, this relatively faint nebula is probably more typical of what is expected in "Crab-like" SNRs than the very bright nebula within the Crab. Furthermore, such nebulae and associated pulsars are probably more easily found in the X-ray band, as was PSR 1509-58, than in the radio. We expect more faint pulsars within SNRs to be discovered in future X-ray observations or from further analysis of present data, and an accurate description of the nebula surrounding PSR 1509-58 will be useful to these future investigations.

II. OBSERVATIONS

A full description of the *Einstein Observatory* and its instrumentation is given by Giacconi *et al.* (1979), and a description of the SNR MSH 15-52 by Seward *et al.* (1983, hereafter SHMC). Data used here were from observations listed in Table 1.

The IPC map of the SNR is shown in Figure 1. Data have been smoothed using a Gaussian of $\sigma = 20''$ to enhance faint features. The strong point source at $15^{\text{h}}09^{\text{m}}59^{\text{s}}.5$, $-58^{\circ}56'57''$ (1950) is the pulsar. Fields of view of the two SSS observations are shown as circles. Note that one SSS

TABLE 1
OBSERVATIONS

Instrument	Exposure Time (s)	Date
Solid State Spectrometer (SSS)	2867	1979 Aug 21 ^a
Solid State Spectrometer (SSS)	4301	1979 Aug 22
Imaging Proportional Counter (IPC)	7240	1980 Aug 15
High Resolution Imager (HRI)	6740	1980 Aug 19

^a Pointed at RCW 89.

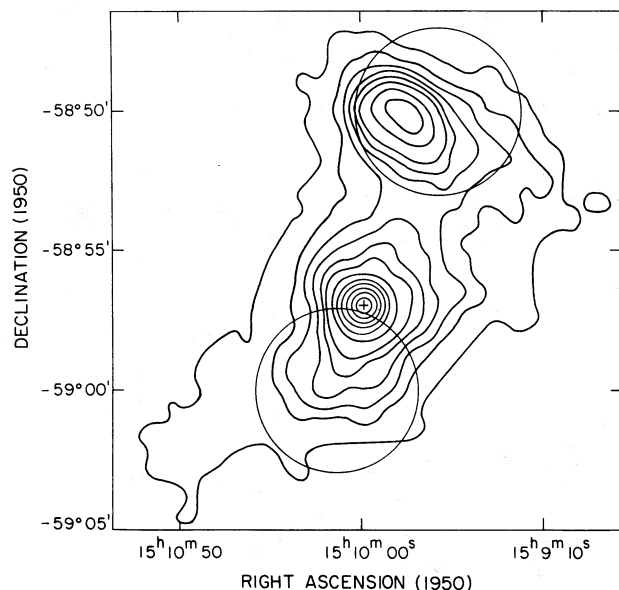


FIG. 1.—Contours of constant X-ray surface brightness of MSH 15-52 derived from the IPC observations. The first six contours are linearly spaced at intervals of $0.0185 \text{ counts s}^{-1} \text{ arcmin}^{-2}$. The remaining contours are spaced at intervals of $0.037 \text{ counts per second per arcminute squared}$. Only the brightest region of the SNR is shown. X-ray emission from the eastern limb of the SNR shell is below the level of the lowest contour shown here. Complete X-ray and radio maps of the SNR are given by Seward *et al.* (1983). The two circles are each $6'$ in diameter and show regions observed by the SSS yielding the spectra shown in Fig. 5 and 6. The cross shows the position of PSR 1509-58.

pointing included about half of the nebula surrounding the pulsar but probably not the pulsar itself, and that the second pointing was at the region of bright optical filaments, RCW 89, on the rim of the remnant (cf. Fig. 4 of SHMC).

III. RESULTS

The IPC map shown in Figure 1 can be used to determine the extent of the nebula around the pulsar. By folding the response function of the *Einstein* telescope and IPC with the emission expected from volumes with particular geometric shapes and filled with uniformly emitting material, the parameters of the various emission regions were determined. The relative strengths and sizes of the different regions were varied until the map shown in Figure 2 was obtained which has the same gross characteristics as those shown in Figure 1. The azimuthal brightness profiles predicted by the model were also required to closely follow the observations illustrated in Figure 1. A χ^2 fitting procedure was not employed because systematic errors were larger than the statistical errors illustrated in the figure. To reproduce the pulsar and surrounding nebula, two components were required: (1) a pointlike source at the position of the pulsar, and (2) a large volume extended source, ellipsoidal in projected shape, of major diameter $10'$ and minor diameter $6'$ and centered at the pulsar position. Table 2 summarizes the model parameters used. The model was required to predict the flux observed by the IPC and to reproduce the general morphology of the bright regions as determined by subjective comparison, but it does not reproduce the small scale structure of Figure 1.

We know from the HRI observation that radiation from the pulsar itself is formally $\geq 80\%$ (and perhaps 100%) pulsed. For purposes of this discussion we assume that all radiation

from the pulsar is pulsed. The pulsed flux measured by the IPC, however, is only half the flux required for the pointlike component by the model that reproduces the spectral structure. The IPC data, therefore, lead to the need for three model components: (1) 10% of the counts are pulsed from the pulsar itself; (2) 10% of the counts are from a region (diameter $\sim 1'$ unresolved by the IPC) of steady emission at the position of the pulsar; and (3) 80% of the counts are from a large nebula, the projection of which is an ellipse of major diameter $10'$, minor diameter $6'$, and the position angle of the major axis is 155° (counterclockwise rotation from north).

Figure 3 shows predicted surface brightness along a major and minor axis of the nebula. Emission from the pointlike components produces the maximum at the position of the pulsar. Data points compared to the major axis prediction were obtained from an octant averaged between position angles 135° and 180° (SE to S). Data points compared with the minor axis prediction were obtained from two octants averaged between 45° and 90° (NE to E) and 225° to 270° (SW to W).

A model was also obtained for RCW 89 (the bright region N of the pulsar), which was observed by SHML to be a region of diffuse emission surrounding two bright knots. The results illustrated in Figure 2 were produced by a model containing two pointlike components separated by $1'$ and aligned along the major axis of an ellipsoidal emission region of projected major diameter $9'$ and minor diameter $3.6'$. The pointlike components are not centered in this larger emission region. No attempt was made to model weak X-ray emission from other parts of the shell of MSH 15-52 such as is evident in Figure 1 SE of the pulsar.

Figure 4 shows a radial profile of the surface brightness around the pulsar measured with the HRI. Emission from the large nebula around the pulsar is faint but can be seen when integrated over 360° in azimuth. The pulsar appears as a

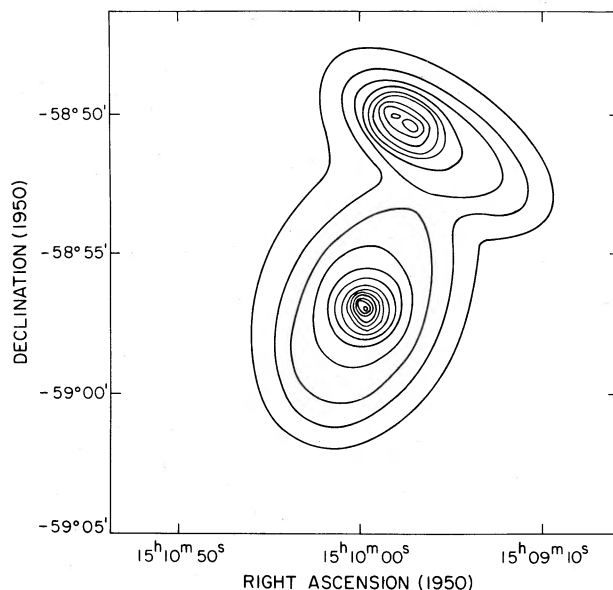


FIG. 2.—Contours of constant X-ray surface brightness produced by folding a model of the source emitting volume with the IPC response function. Contour values and spacing are the same as in Fig. 1. Diffuse emission from around PSR 1509-58 and from RCW 89 have been modeled.

TABLE 2
COMPONENTS USED TO MODEL IPC DATA FOR MSH 15-52

Section of Remnant	Component	Major Diameter	p.a. Major Axis	Minor Diameter	Center ^a (1950)	Strength (IPC c/s)	$L_x(0.2-4 \text{ keV})^b$ (ergs s ⁻¹)
Pulsar	point (pulsed)	...	...	...	15 ^h 09 ^m 59 ^s -58°56'9"	0.12	$1.9 \times 10^{34} \text{ c}$
Synchrotron	pointlike (nonpulsed)	...	...	...	15 ^h 09 ^m 59 ^s -58°56'9"	0.12	$1.9 \times 10^{34} \text{ d}$
Synchrotron	ellipsoid	10'	155°	6'	15 ^h 09 ^m 59 ^s -58°56'9"	0.92	$1.5 \times 10^{35} \text{ d}$
RCW 89	pointlike	...	...	...	15 ^h 09 ^m 52 ^s -58°50'0"	0.11	$4.6 \times 10^{34} \text{ e}$
RCW 89	pointlike	...	...	...	15 ^h 09 ^m 46 ^s -58°50'5"	0.11	$4.6 \times 10^{34} \text{ e}$
RCW 89	ellipsoid	9'	55°	3'6"	15 ^h 09 ^m 38 ^s -58°51'1"	0.55	$2.3 \times 10^{35} \text{ e}$
Total: two bright regions						1.93	5.1×10^{35}

^a IPC locations accurate only to $\sim 1'$.

^b Correcting for absorption of $N_H = 9 \times 10^{21} \text{ atoms cm}^{-2}$.

^c Power law $\alpha = 1.0$.

^d Power law $\alpha = 1.6$.

^e Thermal $kT = 0.3$.

point source superposed on faint emission from the large nebula and upon the general background of the HRI. The pulsed count rate of the HRI is known, and a signal of this intensity, folded with the detector response to a point source (of assumed energy 3.0 keV) is also shown in the figure. There is a region of high brightness extending about 50" from the pulsar, which is not attributable to the sum of the point source and the large nebula. This is further evidence for the existence of a nonpulsed, pointlike component, as required to fit the IPC data. The assumption of a spherical region of radius 60" reproduces the observed excess. There are insufficient counts to determine the shape.

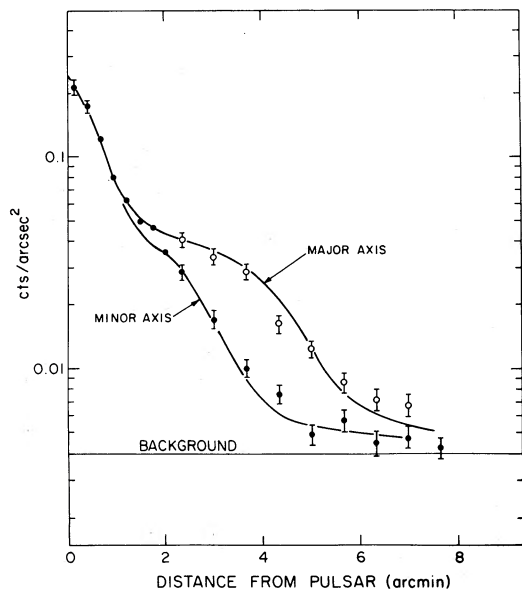


FIG. 3.—Observed IPC surface brightness of nebula surrounding PSR 1509-58 compared with model predictions. Solid curves show calculated brightness from point source plus an ellipsoid with projected major and minor diameters of 10' and 6', respectively. Data points are from regions described in text.

Figures 5 and 6 show SSS spectra obtained from the two circular fields shown in Figure 1. The SSS was not exactly at the focus of the telescope, so the image of a point source was spread over $\sim 1 \text{ mm}^2$ of the detector surface. The boundaries of the field of view, therefore, are not sharp but fuzzy, with an extent of approximately ± 0.5 . Note that PSR 1509-58 lies in this boundary region. The pulsar was barely detectable when the SSS counts were sorted by phase, but no spectrum can be obtained from the pulsar itself, and it does not contribute significantly to the SSS spectrum. Thus this SSS observation (accomplished without knowledge of the pulsar or inner structure of the SNR) gives an accurate spectrum of the southeastern half of the nebula. The X-ray luminosity of the region observed ($\sim$ one-half of the nebula), for a distance of 4.2 kpc and corrected for

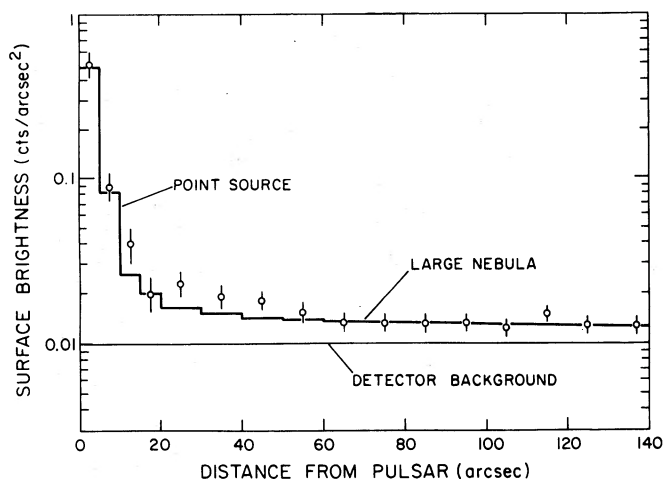


FIG. 4.—Surface brightness surrounding PSR 1509-58 as measured with the HRI. Brightness in each radial bin has been integrated over 360°. Solid lines show background measured outside nebula plus the response to the 6' x 10' elliptical nebula. Histogram shows the added response to a point source.

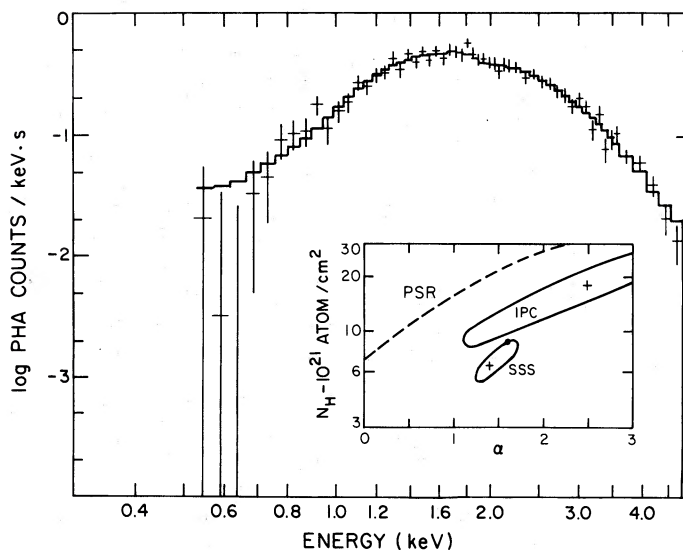


FIG. 5.—SSS pulse height spectrum from region south of PSR 1509-58. Error bars on data points are 1σ counting statistic uncertainties. Histogram shows detector response to best fit power law with $\alpha = 1.40$ and $N_H = 6.3 \times 10^{21}$ atoms cm^{-2} . Insert shows 90% confidence contour for spectral parameters for both SSS and IPC. Solid circle shows values adopted for further analysis. Acceptable values for the pulsar alone lie above the dashed line showing radiation from the pulsar is harder than that from the surrounding region.

interstellar absorption, is 8×10^{34} ergs s^{-1} . Figure 5 shows that the diffuse nebulosity is hard and well fitted by a power law (photon flux $= AE^{-\alpha}$) with index $\alpha = 1.4^{+0.4}_{-0.2}$ and hydrogen column density $N_H = 6.6^{+2.4}_{-1.2} \times 10^{21}$ cm^{-2} . This column density is lower than that of 1.0×10^{22} adopted by SHMC and is at the lower boundary of acceptable fits to the IPC data.

Results of fitting IPC and SSS spectra are summarized in Table 3. The uncertainties given in the table indicate the extremes of rectangles which circumscribe the 90% confidence (two-parameter) contours, as illustrated in Figure 5. Note that the area enclosed by the actual contours is much less than the area of the corresponding "error rectangle."

Table 3 and Figure 5 show that good fits to IPC spectra always require more N_H than good fits to SSS spectra.

The reason for this is not known, but we note that the IPC spectrum includes the entire nebula around PSR 1509-58 and the SSS spectrum only the southern half. The inclusion of the region immediately around the pulsar may account for the IPC measured spectrum being harder than that measured by the SSS. For analysis of the nebula we adopt 9×10^{21} atoms cm^{-2} as the column density and 1.6 as the spectral index. This is the maximum column density acceptable to the SSS, which, because of higher resolution, should be more accurate than the IPC.

Using the IPC data, the spectrum of the pulsar was separated from that of the surrounding nebulosity by sorting according to pulsar phase. Subtraction of "pulsar off" from "pulsar on" gives the spectrum of pulsed events only, and

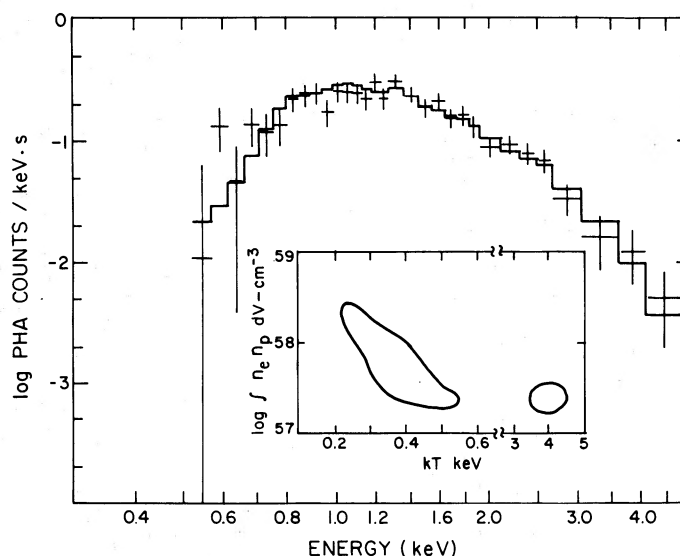


FIG. 6.—SSS pulse height spectrum for RCW 89. Histogram shows detector response to two-component thermal model with $kT_1 = 0.3$ keV, $kT_2 = 4$ keV and $N_H = 9 \times 10^{21}$ atoms cm^{-2} . With N_H fixed at this value which is reasonable for the synchrotron source, both emission measure and temperature are free to vary and the insert shows 90% confidence contours for these two components.

TABLE 3
SUMMARY OF SPECTRAL FITS

Parameter	SSS	IPC
Synchrotron Nebula: Power Law		
α	1.5 ± 0.25	2.5 ± 1.3
N_H (cm^{-2})	$7 \pm 2(21)$	$2.0 \pm 1.1(22)$
χ^2/ν	42/51	12/10
Synchrotron Nebula: Thermal Continuum		
kT (keV)	>7	>4
N_H (cm^{-2})	$7 \pm 2(21)$	$2 \pm 1(22)$
χ^2/ν	43/51	17/12
RCW 89: Power Law		
α	3.0 ± 0.5	6.5 ± 3.0
N_H (cm^{-2})	$4 \pm 1.5(21)$	$2.2 \pm 1.4(22)$
χ^2/ν	53/51	12/12
RCW 89: Thermal		
kT (keV)	1.3	1.2 ± 1
N_H (cm^{-2})	2.4(21)	$1.7 \pm 1.3(22)$
χ^2/ν	97/51	13.5/12
RCW 89: Two-Component Thermal		
kT high (keV)	4 ± 0.5	4
kT low (keV)	0.4 ± 0.15	0.3
N_H (cm^{-2})	9 (21) (fixed)	$2.2 \pm 0.5(22)$
χ^2/ν	48/49	12.5/12

the "pulsar off" data give the synchrotron nebula only. Figure 5 shows the range of acceptable parameters for power-law fits. As in the Crab Nebula, the pulsed emission is harder than the surrounding nebular emission, but the pulsed spectral index is not determined at all accurately. The pulsed X-ray luminosity using a distance of 4.2 kpc, a spectral index of 0.5, and correcting for interstellar absorption in 9×10^{21} atoms cm^{-2} is 1.7×10^{34} ergs s^{-1} . This index only applies to the energy range 0.5–4 keV and must steepen at higher energies to keep the total pulsed luminosity from being too large.

The SSS data are also well fitted by a thermal continuum characterized by $kT = 11$ keV, $N_H = 9 \times 10^{21}$, and the fit is about as good as that of a power law. The temperature is high enough so most of the energy would be radiated as continuum radiation. The ~ 6.8 keV Fe line, however, should be prominent with an equivalent width of 700 eV (for $\text{Fe}/\text{H} = 4 \times 10^{-5}$). Data from *OSO 8* and *HEAO 1 A-2* establish $< 7 \times 10^{-4}$ Fe line photons $\text{cm}^{-2} \text{s}^{-1}$ and equivalent width (with respect to the total continuum) < 350 eV (Robinson-Saba 1983). This absence of an observed Fe line strengthens our conclusion that the nebula arises from synchrotron emission.

Figure 6 shows the SSS pulse height spectra for RCW 89. The fit illustrated is a two-component thermal spectrum with low temperature $kT = 0.3$ keV, high temperature $kT = 4$ keV, $N_H = 9 \times 10^{21}$ atoms cm^{-2} and $\chi^2 = 48$ for 49 dof. The best single-temperature fit to this spectrum gives $kT = 1.3$ keV, $N_H = 4 \times 10^{21}$, but with $\chi^2 = 97$ for 51 dof, which is clearly unacceptable. The best fit power law is $\alpha = 3.0 \pm 0.5$, $N_H = 3 \times 10^{21}$, with $\chi^2 = 55$ for 51 dof. Low column density of this latter fit leaves the two-component

thermal model as the best choice. The X-ray luminosity of RCW 89, corrected for interstellar absorption and under the assumption of the two-component thermal model, is 3.9×10^{35} ergs s^{-1} . This agrees, within calibration uncertainties, with the IPC derived luminosity of 3.2×10^{35} ergs s^{-1} listed in Table 2.

Below 1.2 keV, 70% of the counts are due to the 0.3 keV component where line emission dominates. Our model includes these lines, but they are too closely spaced to be resolved by the SSS. The strongest line complexes predicted are from Fe XVII at ~ 0.82 keV, Ne IX ~ 0.92 keV, and Mg XI at ~ 1.34 keV, with respective fluxes of 20, 7, and 2×10^{-5} photons $\text{cm}^{-2} \text{s}^{-1}$. A small maximum at ~ 1.3 keV from the Mg XI line complex can be seen in the model fit to the pulse height spectrum of RCW 89.

Figure 7 shows the photon spectra (smoothed over the detector energy response) resulting from both SSS observations and from the monitor proportional counter (MPC) which was pointed along the telescope axis. The square MPC field of view of 42' FWHM included the entire SNR. The solid curve shows the sum of the SSS results after multiplying the spectrum of the synchrotron nebula by 2 (since only half of this region was in the SSS field of view). Thus the synchrotron nebula accounts for nearly all of the emission above 2 keV. The pulsar itself is expected to add another $\sim 10\%$. At energies below 1.5 keV, there is a MPC excess above the solid line, probably due to soft thermal radiation from the shell which SHMC estimate contributes 21% of the IPC counting rate.

The spectrum indicated by the solid line is softer than the spectrum derived from *Ariel V* observations by Chiappetti and Bell-Burnell (1982). Our measured photon flux is a factor of 3 higher than theirs at 2 keV and about the same above 5 keV.

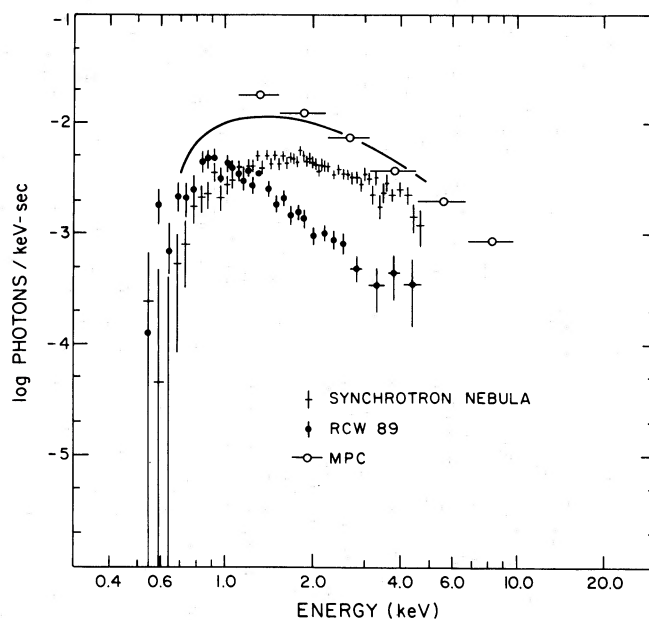


FIG. 7.—SSS-derived photon spectra for the two regions. Crosses are for the region south of PSR 1509–58, solid points are for RCW 89, and open circles show the spectrum measured by the MPC when pointed at the pulsar. Solid line is sum of RCW 89 and 2 times the synchrotron spectrum.

IV. DISCUSSION

At the time of this writing there are three SNR known to contain a radio pulsar surrounded by diffuse X-ray emission: the Crab Nebula, Vela X, and MSH 15-52. The pulsar periods are all increasing with time, and the consequent loss of rotational kinetic energy is enough in each remnant to power a synchrotron nebula with the observed luminosity and volume. The nebula within MSH 15-52 is more clearly visible than the postulated nebula within the Vela remnant. Thermal X-ray emission from the Vela remnant is strong, and low surface brightness synchrotron emission in the vicinity of the pulsar is difficult to identify (Harnden 1983).

A radio map of MSH 15-52 shows only weak emission from the region surrounding the pulsar (Caswell *et al.* 1981), and probably this emission is from the expanding shell. If the synchrotron spectrum of the nebula around PSR 1509-58 were the same as that of the nebula surrounding the Crab pulsar except with the spectral break in the X-ray band (instead of in the optical) where electron lifetime is expected to equal the age of the remnant, the optical brightness can be calculated as approximately 28 mag per square arc minute and the total radio expected as only 10^{-3} Jy. Thus the synchrotron nebula within MSH 15-52 is predicted to be far too faint to be seen at radio and optical wavelengths.

Tables 4 and 5 compare the Crab and MSH 15-52 pulsars and surrounding nebulae. There is no doubt that the diffuse emission from the Crab is synchrotron radiation, since it is strongly polarized at all wavelengths. There are no polarization measurements for the nebula around PSR 1509-58, but the spectrum, which is both hard and free of spectral features, strongly indicates a synchrotron origin.

a) The Crab Nebula

The Crab contains the fastest known pulsar within a SNR and the brightest synchrotron nebula. A good summary is given by Manchester and Taylor (1977), and the proceedings of *IAU Symposium 46* (Davies and Smith 1971) contain observational detail. The distance 2.0 kpc is well determined for a SNR. The nebula is contained within bright optical filaments which, in projection, form a $5' \times 7'$ ellipse. The enclosed volume of 4×10^{57} cm³ is filled by diffuse radio and optical emission. The X-ray nebula, however, is considerably

TABLE 4
PROPERTIES OF CRAB AND MSH 15-52 PULSARS

Property	Crab	MSH 15-52
Distance (kpc)	2.0	4.2
Pulsar	0531+21	1509-58
p (s)	0.033 ^a	0.150 ^d
$\dot{p}$ (10^{-15} s s ⁻¹)	423 ^a	1540 ^d
$\dot{E}$ (ergs s ⁻¹)	4.6(38)	1.8(37)
m (gauss cm ³)	6.7(30)	2.7(31)
Age (yr)	1.23(3)	1.55(3)
Spectral index, α	1.5 ^b	<0.5
L_x (0.2-4 keV) (ergs s ⁻¹)	1(36) ^c	2(34)
C (HRI counts s ⁻¹)	5.0 ^c	0.01

^a Manchester and Taylor 1977.^b Toor and Seward 1977.^c Harnden 1983.^d Weisskopf *et al.* 1983.

TABLE 5

PROPERTIES OF CRAB AND MSH 15-52 SYNCHROTRON NEBULAE

Property	Crab	MSH 15-52
Size (arcmin)	1.4×0.8^a	10×6
V_x (cm ³)	9(54)	1.3(58)
Spectral index, α	2.1	1.6
L_x (ergs s ⁻¹)	2(37) ^b	1.7(35)
H_x (gauss)	2(-4)	7(-6)
τ (yr)	30	5(3)
C (HRI counts s ⁻¹)	109 ^a	0.10 ^c

^a Harnden 1983.^b Toor and Seward 1974.^c IPC counts s⁻¹ $\times$ 0.1.

smaller with angular dimension $\sim 1'$ and volume $\sim 1 \times 10^{55}$ cm³ (Harnden 1983).

Knowing the luminosity, L_x ergs s⁻¹, and the volume, V_x cm³, the magnetic field, H , and energy contained in relativistic electrons, E_p , can be calculated. We assume: (1) the nebula contains a uniform field, (2) the particles all have energy such that maximum synchrotron emission is at 1 keV, and (3) energy in the nebula is equally divided between relativistic electrons and magnetic field.

Then: $H = 25 L_x^{2/7} V_x^{-2/7}$ gauss, $E_p = E_H = V_x H^2 / 8\pi$ ergs, and the radiation lifetime of the electrons is $\tau = 3000 H^{-3/2}$ s.

Measured and calculated properties of the Crab Nebula are listed in Table 5. The X-ray luminosity in the *Einstein* band (0.2-4 keV) is 2×10^{37} ergs s⁻¹, divided 95% from the nebula and 5% from the pulsar.

Since the Crab radiates strongly at all wavelengths ranging from radio to high-energy γ -rays, there is a large population of electrons ignored by the above restriction to the X-ray band. The calculated H and E_H are lower limits. When the entire electromagnetic spectrum is taken into account, $L_{\text{tot}} = 2 \times 10^{38}$ ergs s⁻¹, $H \approx 5 \times 10^{-4}$ gauss, $\tau = 9$ years, and $E_H \approx 1 \times 10^{49}$ ergs. (The volume of the radio and optical nebula is ~ 100 times greater than that of the X-ray nebula, and most of the particle energy is contained in the electrons emitting in the band stretching from the IR to soft X-rays. The high field is required only in the central region, and H may well vary throughout the nebula.)

Thus if X-rays are considered to be the only appreciable radiation, the derived magnetic field is a factor of only 2.5 less than the actual field, but the total energy in particles and fields is grossly underestimated.

If the central pulsar has a strong internal magnetic dipole moment, m , and rotational moment of inertia I (taken as 10^{45} g cm²), and if the period, p , and period derivative, $\dot{p}$, are known; the magnetic moment, the rate of rotational energy loss, and the "characteristic age" of the pulsar are given by: $m = (3c^3 I \dot{p} p / 8\pi)^{0.5}$; $\dot{E} = -4\pi^2 I \dot{p} / p^3$; and $A = p / 2\dot{p}$ (Manchester and Taylor 1977).

For the Crab Pulsar p is the third smallest (as of 1983 September) of any of the ~ 300 known radio pulsars and $\dot{p}$ is the second largest, so $\dot{E}$ is high and A is small. The value of $\dot{E} \approx 5 \times 10^{38}$ ergs s⁻¹, so the pulsar can supply the energy necessary to maintain the luminosity of the synchrotron nebula, and the efficiency of transferring rotational energy to radiation is ~ 0.4 . If soft X-rays were the only radiation observed, this efficiency would appear to be only 0.06.

The characteristic age of the pulsar, 1230 years, is slightly

larger than the known SNR age of 920 years. The magnetic moment corresponds to a surface field of $\sim 10^{13}$ gauss.

b) MSH 15-52

The X-ray and radio pulsar in MSH 15-52 is surrounded by diffuse X-ray emission and shows promise of being truly Crab-like: a synchrotron nebula powered by spin-down of a central pulsar. The synchrotron origin for the nebular X-rays cannot be firmly established using only the spectral observations. However, the spatial symmetry about the pulsar and the observed lack of comparable hot interiors in other young shell-like SNRs lead to this conclusion.

The pulsar period of 150 ms is not unusually rapid. The period derivative, however, is 3 times higher than that of the Crab pulsar (Table 3) and the highest of any radio pulsar: $\dot{E} = 2 \times 10^{37}$ ergs s^{-1} ; $m = 3 \times 10^{31}$ cm ^{3} ; and $A = 1550$ years. Thus the pulsar is only slightly older than the Crab pulsar, has a magnetic moment 3 times higher, and is losing energy at $\sim 1/30$ the rate.

The X-ray nebula observed is much larger than that surrounding PSR 0531+21 but not as luminous. The nebula fills a volume of $1.3 \pm 0.3 \times 10^{58}$ cm $^3 \approx (450 \text{ pc}^3)$; the uncertainty given is the difference between choosing a prolate or an oblate spheroid for the shape. The observed X-ray luminosity of 1.7×10^{35} ergs s^{-1} is only ~ 0.01 of $\dot{E}$, so the pulsar easily supplies the necessary energy. The calculated nebular magnetic field is a factor of ~ 20 below that calculated in a similar way for the Crab and characterizes the great difference in X-ray surface brightness. The field in the $6' \times 10'$ nebula is calculated as 0.7×10^{-5} gauss, and the field in the $2'$ diameter core as 1.2×10^{-5} gauss. The field close to the pulsar is apparently larger than the average field in the $6' \times 10'$ nebula. In the discussion to follow we will speak of only the $6' \times 10'$ nebula and ignore the $2'$ core. This region close to the pulsar is certainly worthy of further study, but more detailed observations are needed. One possibility that should be investigated is scattering from interstellar dust. The pulsar should be surrounded by a halo of scattered X-rays which are no longer pulsed, since path lengths vary by many pulsar cycles. Catura (1983) has observed dust-scattered halos around strong galactic sources, but only 15%–20% of the X-rays are in the halo compared to a possible 50% around PSR 1509–58.

The size of the $6' \times 10'$ nebula compared to the Crab can be explained by considering the large envelope of MSH 15-52, which has allowed the pulsar-supplied magnetic field to expand more freely, resulting in a larger, less luminous nebula. This is probably the usual situation and a search for Crab-like objects should find many like MSH 15-52 and few as bright as the Crab. We do know that there are no other sources as bright as the Crab in our Galaxy.

c) A Simple Model

How do the magnetic fields calculated for the synchrotron nebulae compare with expectations? Consider the following simple model. A spherical SNR of radius R contains a central pulsar with rate of rotational energy loss $\dot{E}$. This energy input is equally divided between magnetic field and relativistic charged particles. The dynamics of the shell are determined by the initial explosion and the ISM rather than by internal energy deposited by the pulsar. Expansion of the remnant is adiabatic, and the field is randomly ordered,

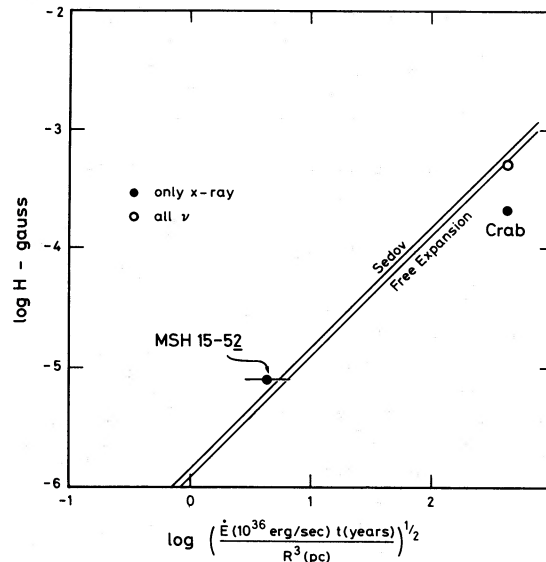


FIG. 8.—Predicted magnetic field within a model SNR compared with field calculated from X-ray observations. Solid points assume electron population such that radiation peaks in X-ray band. Open circle includes radiation observed at other wavelengths.

so magnetic pressure is $B^2/24\pi$. Conservation of energy gives $3\dot{E} = 2BR^3\dot{B} \pm 4B^2R^2\dot{R}$.

If $\dot{E}$ is constant and radiation energy losses are negligible (neither is correct, but the two effects do go in opposite directions and, at this point, we need to understand the gross properties), the solution, written to explicitly contain the age of the remnant, t , is $B = (f\dot{E}t/R^3)^{0.5}$, where f is a constant = $3/2$ if the shell motion is a free expansion and $15/7$ if the remnant is in the Sedov phase.

These examples are plotted as straight lines in Figure 8 and compared with equipartition fields derived from observations. Values of $\dot{E}$ and t are known or calculated from the pulsar properties. The uncertainty shown from MSH 15-52 is due to the irregular nature of the shell, which in the E and S is 18 pc distant from the pulsar, but in the NW (the dense region RCW 89) is only ~ 8 pc distant. As can be seen in the figure, the X-ray derived fields are not far from the fields predicted using the pulsar properties and SNR dimensions. Of course, more data points are needed to test the correctness of this model and to make further development of it worthwhile. Several other SNRs show promise of being Crab-like, but the central pulsars remain to be identified and to have p and $\dot{p}$ measured. More details concerning the model and these SNRs are given by Seward (1983). The following section contains a brief description of several remnants which have or are likely to have associated pulsars.

d) Other Filled-Shell (Plerionic) SNRs and SNRs with Central Objects

In the radio band a number of SNRs have characteristics similar to the Crab: there is no shell-like structure; emission is polarized and maximum at the center; and the radio spectrum is $\sim$ flat. These have been listed and their radio properties studied by Lockhart *et al.* (1977), Weiler and Shaver (1978), and Caswell (1979). Four of these were observed by *Einstein*, and X-ray results are given by Wilson (1980), Becker and Szymkowiak (1981), and Becker, Helfand, and Szymkowiak (1982). Diffuse X-rays were seen from all and,

like the Crab Nebula, X-ray emission was strongest at the center, the diffuse X-ray source was smaller than the radio SNR, and in one case where a good spectrum was obtained (3C 58), there was no evidence for line emission. The X-ray morphology of the central regions of 3C 58 and of CTB 80 is sharply peaked, indicating the existence of a central source, and accurate locations for these sources were obtained. No pointlike X-ray sources could be separated from the diffuse emission observed from G21.5-0.9 or from $G74.9 \pm 1.2$, and upper limits are given. Pulsations were not observed from any of these central regions, but the flux from all the sources is below the threshold for detection of regular pulsations. These SNRs are prime targets for a more sensitive high-resolution instrument.

Vela X contains a radio pulsar with well-determined properties and should be surrounded by a large, faint X-ray synchrotron nebula similar to that around PSR 1509-58. Thermal X-ray emission from the shell is strong, however, and obscures the central region. The synchrotron nebula can probably be distinguished using *Einstein* spectral data, and such an analysis is currently underway.

The remnant RCW 103 has a central pointlike X-ray source and no obvious surrounding synchrotron nebula. The central source is again too weak to reasonably search existing data for regular pulsations, and the apparent absence of a synchrotron nebula would favor radiation from the surface of a hot neutron star or identification as a background object not connected with the remnant. Since the optical candidates for the central source are all very faint, Tuohy and Garmire (1980) favor the neutron star explanation. Emission from the 8' diameter shell, however, produces 300 times more counts in the *Einstein* HRI than does the pointlike source, and this emission from the shell could easily obscure a faint synchrotron nebula.

Both W50 and CTB 109 contain central compact X-ray sources which are members of binary systems. The 3.5 s X-ray pulsar within CTB 109 shows frequency changes indicating orbital motion with a period of 0.6 hours (Fahlman and Gregory 1983). SS 433, in the center of W50, is a bright optical source showing a period of ~ 13 days (Crampton, Cowley, and Hutchings 1980). In these systems, accretion is expected to smother the production of the fields and relativistic electrons which produce Crab-like synchrotron nebulae.

V. CONCLUSIONS

1. The X-ray nebula surrounding PSR 1509-58 is most probably synchrotron radiation and powered by spin-down of the central pulsar. The observed luminosity and volume are quite compatible with the observed pulsar characteristics.

2. The nebula is probably not observable at optical or radio frequencies.

3. The nebula can be compared with the synchrotron nebula around the Crab pulsar using observed properties of the SNR shells. The much higher luminosity and surface brightness of the Crab Nebula is attributed to the high rate of energy loss of the pulsar and the small size of the SNR shell. For both remnants, the magnetic field calculated from the observed synchrotron emission is close to an assumed remnant-filling field supplied by pulsar spin-down energy.

This work was largely supported under NASA contract NAS8-30751, and some analysis was accomplished at the Institute of Astronomy, Cambridge, England. F. D. S. would like to thank the Institute of Astronomy for their support and hospitality.

REFERENCES

- Becker, R., Helfand, D., and Szymkowiak, A. 1982, *Ap. J.*, **255**, 557.
 Becker, R., and Szymkowiak, A. 1981, *Ap. J. (Letters)*, **248**, L23.
 Caswell, J. L. 1979, *M.N.R.A.S.*, **187**, 431.
 Caswell, J. L., Milne, D. K., and Wellington, K. J. 1981, *M.N.R.A.S.*, **195**, 89.
 Catura, R. C. 1983, *Ap. J.*, **275**, 645.
 Chiappetti, L., and Bell-Burnell, S. J. 1982, *M.N.R.A.S.*, **200**, 1025.
 Crampton, D., Cowley, A., and Hutchings, J. 1980, *Ap. J. (Letters)*, **235**, L131.
 Davies, R. D., and Smith, F. G., eds. 1971, *IAU Symposium 46, The Crab Nebula* (Dordrecht: Reidel).
 Fahlman, G., and Gregory, P. 1983, in *IAU Symposium 101, X-Rays from Supernova Remnants*, ed. P. Gorenstein and J. Danzinger (Dordrecht: Reidel), p. 445.
 Giacconi, R., et al. 1979, *Ap. J.*, **240**, 333.
 Harnden, F. R., Jr. 1983, *IAU Symposium 101, X-Rays from Supernova Remnants*, ed. P. Gorenstein and J. Danzinger (Dordrecht: Reidel), p. 131.
 Lockhart, J. A., Goss, W. M., Caswell, J. L., and McAdam, W. B. 1977, *M.N.R.A.S.*, **179**, 147.
 Manchester, R. N., and Taylor, J. H. 1977, *Pulsars* (San Francisco: W. H. Freeman and Co.).
 Manchester, R. N., Tuohy, I., and D'Amico, N. 1982, *Ap. J. (Letters)*, **262**, L31.
 Robinson-Saba, J. 1983, Ph.D. thesis, University of Maryland.
 Seward, F. 1983, in *IAU Symposium 101, X-Rays from Supernova Remnants*, ed. P. Gorenstein and J. Danzinger (Dordrecht: Reidel), p. 405.
 Seward, F. D., and Harnden, F. R., Jr. 1982, *Ap. J. (Letters)*, **256**, L45.
 Seward, F. D., Harnden, F. R., Jr., Murden, P., and Clark, D. H. 1983, *Ap. J.*, **267**, 698 (SHMC).
 Toor, A., and Seward, F. D. 1974, *A.J.*, **79**, 995.
 ———, 1977, *Ap. J.*, **216**, 560.
 Tuohy, I., and Garmire, G. 1980, *Ap. J. (Letters)*, **239**, L109.
 Weiler, K. W., and Shaver, P. A. 1978, *Astr. Ap.*, **70**, 389.
 Weisskopf, M. C., et al. 1983, *Ap. J.*, **267**, 711.
 Wilson, A. S. 1980, *Ap. J. (Letters)*, **241**, L19.

FRANK R. HARNDEN, JR., and FREDERICK D. SEWARD: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

JEAN H. SWANK and ANDREW SZYMKOWIAK: Code 661, Goddard Space Flight Center, Greenbelt, MD 20771