

MSH 15–52: A SUPERNOVA REMNANT CONTAINING TWO COMPACT X-RAY SOURCES

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ABSTRACT

Einstein observations show two small-diameter, bright X-ray sources within the shell of the Galactic radio supernova remnant (SNR) MSH 15–52. X-ray spectra and optical extinction indicate that both compact sources are at least as distant, 4.2 kpc, as the diffuse emission from the shell. There is also enhanced, diffuse emission in the vicinity of both compact sources, as well as coincident with the radio shell. The source closest to the middle of the remnant is hard, is unresolved by the HRI, was previously detected as 4U 1510–59, and shows strong regular X-ray pulsations with a period of 0.150 s. The second source is associated with a collisionally excited, high-density, optical knot within the $H\alpha$ nebula RCW 89 close to the northwestern rim of the SNR.

CCD observations with the Anglo Australian Telescope yield possible reddened candidates for 4U 1510–59 and map the optical knot. Infrared spectral lines at $1.6\ \mu\text{m}$ of [Fe II] appear in the knot. This is the first time these lines have been seen in an SNR; they are at an intensity comparable to the Balmer emission. UK Schmidt telescope photographs of RCW 89 show new filaments which extend into MSH 15–52 and support the hypothesis that the $H\alpha$ nebula is part of the whole SNR.

It is difficult to incorporate the apparently young pulsar (characteristic age ~ 1600 years), the apparently old SNR ($> 10,000$ yr), and the bright knot into a single consistent system. We discuss the interaction of the supernova ejecta with the interstellar medium (which determines the X-ray, optical, and radio appearance of the shell), the possibility that the ages of the pulsar and the SNR are less discrepant than they first appear, and the possibility that a second pulsar powers the knot and RCW 89.

Subject headings: nebulae: individual — nebulae: supernova remnants — pulsars —
 radio sources: extended — X-rays: sources

1. INTRODUCTION

MSH 15–52 is an extended nonthermal radio source in Circinus centered $1^{\circ}2'$ below the galactic plane and was first listed in the catalog of Mills, Slee, and Hill (1961). Radio maps at 408 MHz and 5000 MHz are given by Shaver and Goss (1970) and Haynes, Caswell, and Simon (1978), respectively. Recently Caswell, Milne, and Wellington (1981) have mapped the emission at 1415 MHz with a resolution of $\sim 1'$. The gross features of all these radio maps are similar. There are two elongated arcs of emission separated by $\sim 20'$ which can, without difficulty, be imagined as being on the rim of a supernova remnant (SNR) shell of diameter $25'–30'$. The NW arc is brighter than the SE, and the brightest

portion, G320.4–1.0, a region $\sim 10'$ in diameter, has been listed as the radio source Kes 23 (Kesteven 1968) and coincides with the $H\alpha$ emission nebula RCW 89 (Rogers, Campbell, and Whiteoak 1960).

The $10'$ diameter radio bright spot and the SE arc have been distinguished as separate SNRs by Milne (1970) and by Downes (1971). Van den Bergh, Marscher, and Terzian (1973) have listed RCW 89 as an optical SNR and have published a broad-band red exposure showing a circular network of brighter filaments comprising the bright part of this remnant. They opine that RCW 89 is not to be identified with MSH 15–52. On the other hand, recent radio-based catalogs (Clark and Caswell 1976) list one SNR, MSH 15–52, incorporating the RCW 89 bright spot into the NW rim of the larger

remnant. The high-resolution map by Caswell, Milne, and Wellington (1981) also suggests that the two structures are part of a single remnant.

Caswell *et al.* (1975) have measured the neutral H I absorption profile of the radio source G320.4-1.0 (Shaver and Goss 1970) which is the strongest part of MSH 15-52 and associated with RCW 89. The source shows interstellar absorption which comes from material out to 4.2 kpc but not material corresponding to the next spiral arm at 8 kpc. The Σ - D relation (Clark and Caswell 1976) yields 4.4 kpc for the distance of the remnant, regarding it all as one object, and we henceforth adopt the more reliably determined minimum kinetic distance of 4.2 kpc as the distance of MSH 15-52.

II. X-RAY OBSERVATIONS

Cowley and MacConnell (1972) showed that there was a coincidence between an X-ray source, 2U 1509-58, and the SNR. The *Uhuru* error box, which contained RCW 89, was later refined southward so that the error box of the X-ray source 4U 1510-59 (Forman *et al.* 1978) covered the center of the SNR, midway between the NW and SE arcs. Doubt was thrown on the identification of 4U 1510-59 with the spatially extended SNR by a null *Copernicus* observation (Zarnecki *et al.* 1975) of the RCW 89 area, although the possibility remained that 4U 1510-59 was a point X-ray source within the SNR, perhaps the stellar remnant of the supernova explosion, like the Crab and Vela pulsars, the point X-ray source in RCW 103, or SS 433 in W50.

The area of 4U 1510-59 and MSH 15-52 was observed four times by the *Einstein* imaging detectors (for a description of the instrumentation, see Giacconi *et al.*

1979). Two spectra were also obtained with the solid state spectrometer (SSS) and will be more fully described in a separate paper. Maps with $\sim 1'$ resolution were obtained with the imaging proportional counter (IPC) 1979 August 25 and 1980 August 15. The high-resolution imager (HRI) was used on 1979 August 24 and 1980 August 19 to observe the brightest portion of the SNR.

Figures 1a and 1b compare the IPC image with the HRI image. Note the two bright point-like sources, which we refer to as the north (N) source and south (S) source. There is also a third source NE of the remnant, the east (E) source. Figures 2a and 2b show the 8000 s IPC exposure separated into different energy bands which emphasize soft and hard X-rays. Source S is clearly emitting the most hard photons from this region.

Both HRI exposures show source N and source S clearly. The field of view did not include source E, and the diffuse emission surrounding sources N and S, which is so prominent in the IPC data, does not appear above background in the HRI exposure. Source S appears unresolved, with its core FWHM of $\sim 4''$ corresponding to the expected instrument response to a point source. Source N is resolved into two components (difficult to see in Fig. 1b but clear in Fig. 6a) here called northeast (NE) and northwest (NW). There is also a faint ridge of emission extending east-west which includes both these bright condensations. The brighter (NE) knot has FWHM of $\sim 10''$, and unfolding the telescope instrumental broadening yields a diameter of $11'' \pm 2''$ for this X-ray emitting condensation. Henceforth we will treat it as a knot or clump of material rather than as a point source.

X-ray emission from source S is strongly pulsed, and the discovery of pulsations and the characteristics of the

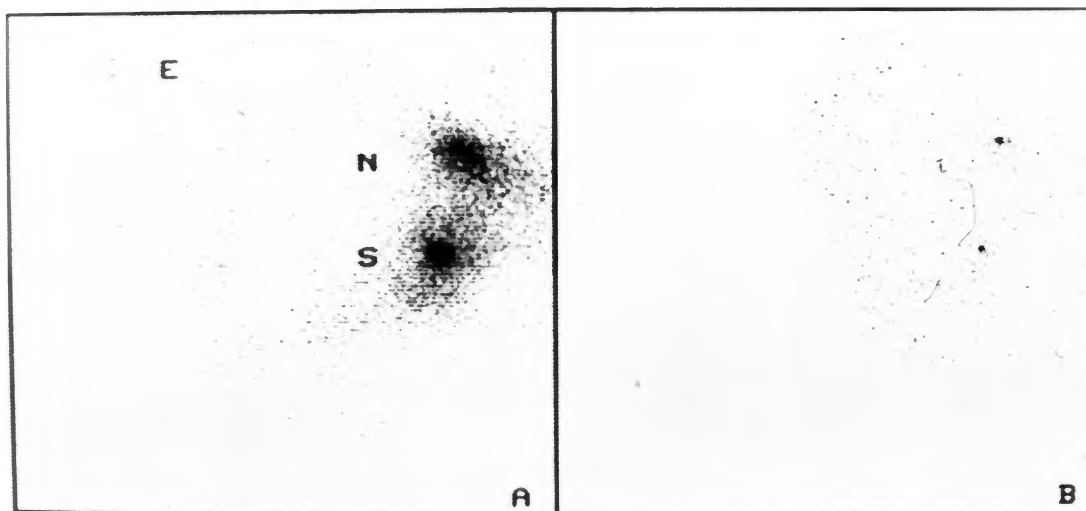


FIG. 1.—(a) IPC image of MSH 15-52 in the energy range 0.2–2.8 keV showing two bright diffuse regions surrounding two pointlike sources. The field is $34'$ square. (b) HRI image to same scale showing the two compact sources.

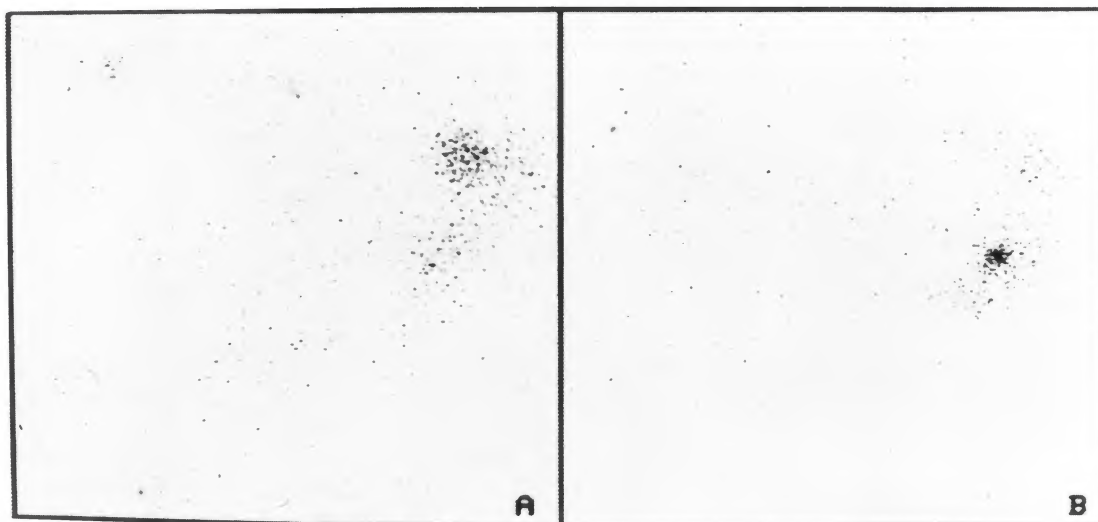


FIG. 2.—IPC images of MSH 15–52 in two energy bands, (a) pulse heights < 0.8 keV, (b) pulse heights > 2.8 keV. Note source E is soft and S is hard. Both fields are $34'$ on each side.

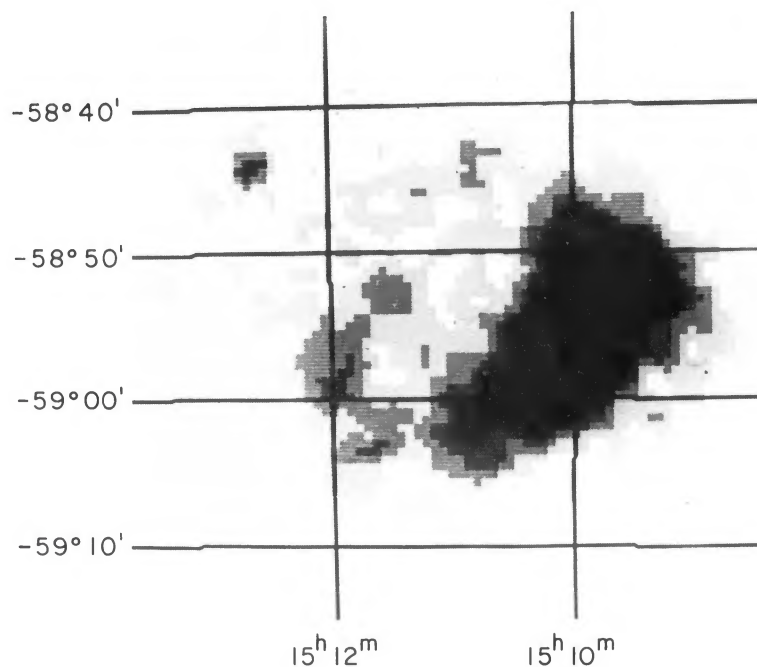


FIG. 3.—IPC image smoothed to show diffuse emission. Bright regions surrounding sources N and S are overexposed.

pulsar are discussed by Seward and Harnden (1982). Briefly, the object exhibits one X-ray pulse per cycle, the FWHM of the pulse is one-fourth of the cycle and the pulsed fraction is at least 80%. The barycentric period measured 1979 August 25 was $0.150094 \text{ s} \pm 1 \text{ } \mu\text{s}$, and the period measured 1980 August 15 was $0.150140 \text{ s} \pm 1 \text{ } \mu\text{s}$. Thus, the increase of period with time, $\dot{P}$, if interpreted as a secular increase, was $47 \pm 2 \text{ } \mu\text{s}$ per year or $1.49 \times 10^{-12} \text{ s s}^{-1}$. As a consequence of this high value

of $\dot{P}$, the characteristic age of the pulsar, $P/2\dot{P}$, is only 1600 years, and the rate of loss of rotational energy, $-4\pi^2 I \dot{P}/P^3$, is $\sim 2 \times 10^{37} \text{ ergs s}^{-1}$. The pulsar has recently been detected at 1.4 GHz, and the high period derivative has been confirmed, by Manchester, Tuohy, and D'Amico (1982).

In Figure 3, the IPC data have been smoothed using a Gaussian function with $\text{FWHM} = 1.5$ and the background subtracted to show diffuse emission. The two

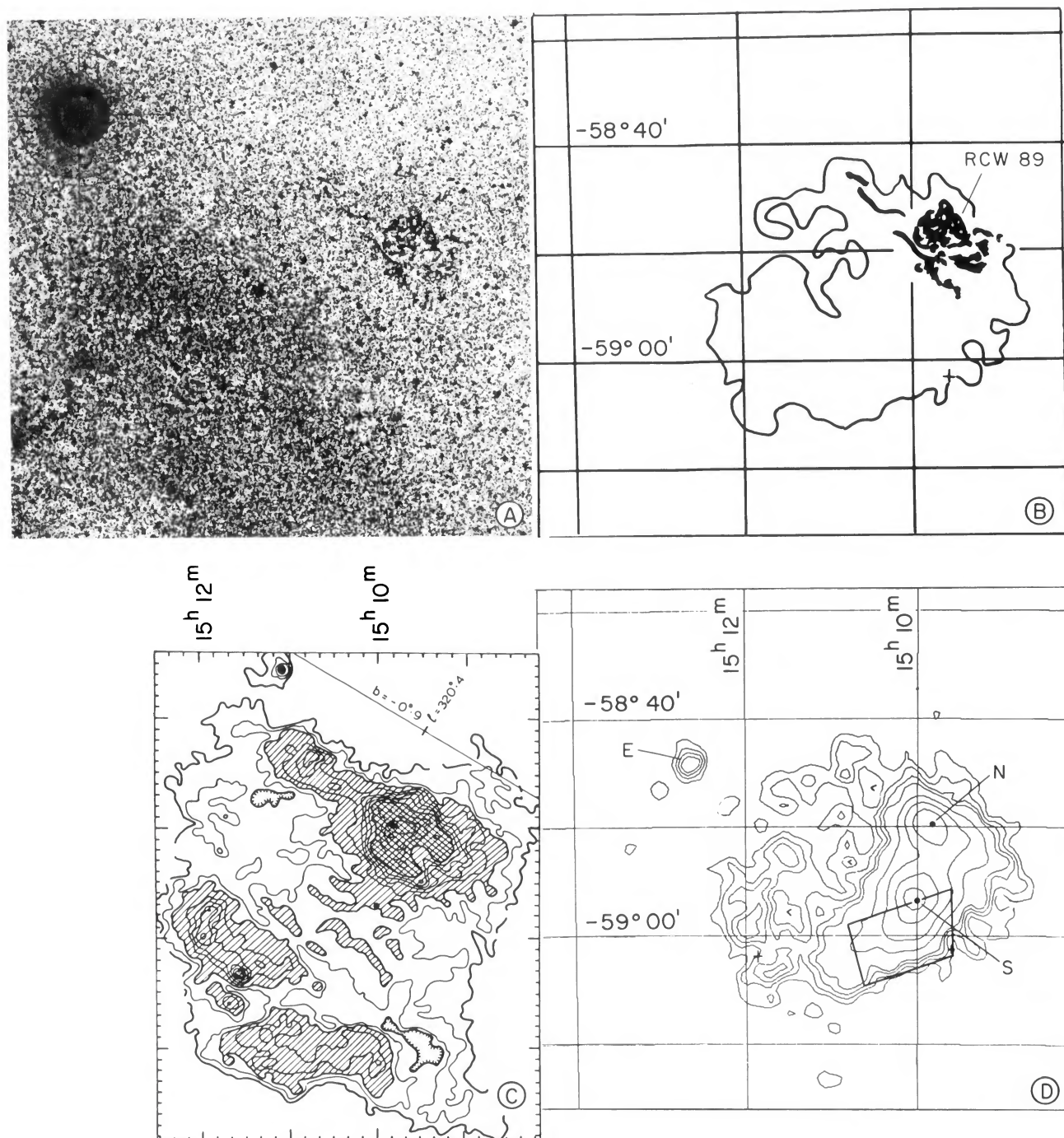


FIG. 4.—(a) Enhanced contrast print by David Malin (AAO) of same area as Fig. 4d on an *R*-band UK Schmidt Telescope picture, showing filament 9' NE of RCW 89. The bright star is 4th mag β Cir. (b) Outermost X-ray contour of Fig. 4d with optical filaments shown schematically. (c) Fleurs radio map (Caswell *et al.* 1981). The positions of sources N and S are indicated by filled circles. (d) Contours of constant X-ray surface brightness from IPC. The positions of sources N and S and the error box for 4U 1510–59 are indicated. Data are from Fig. 3. First four contours are linear in units of ~ 0.001 counts s^{-1} arcmin $^{-2}$, after fourth contour there is a factor of 2 between adjacent contours. Figs. 4a–4d are all to the same scale. Coordinates are epoch 1950.

TABLE 1
LOCATION OF X-RAY SOURCES

Source Name	Designation Used Herein	R.A.	Decl.	Error Circle Radius
1E 150946–5849.6 ...	NW	15 ^h 09 ^m 46 ^s .2	–58°49′37″	5″
1E 150950–5849.6 ...	NE	15 09 50.5	–58 49 39	5″
1E 150959–5856.9 ...	S	15 09 59.5	–58 56 57	5″
1E 1512.6–5843	E	15 12 37.3	–58 43 57	60″

TABLE 2
X-RAY SOURCE CHARACTERISTICS

Detector	Source	Count Rate (counts s ^{–1})	N_H (cm ^{–2})	Index	0.2–4 keV Flux ^a (ergs cm ^{–2} s ^{–1})	X-Ray Luminosity L_x ^b 0.2–4 keV
IPC	E	0.041	low	$kT = 0.6$	8.0(–13)	9(31) if 1 kpc distant
IPC	N	0.26 ^c	1.2(22)	$kT = 1.2$	7.2(–12) ^c	7.1(34) ^c
IPC	S	0.31 ^c	1.2(22)	$\alpha = 1.7$	1.5(–11) ^c	8.3(34) ^c
HRI	NE	1.2(–2)	...	...	1.2(–12)	2.0(34)
HRI	NW	0.3(–2)	...	...	0.3(–12)	0.7(34)
HRI	S	1.0(–2)	...	...	1.0(–12)	4.0(34)
IPC	Diffuse surrounding:					
	N source	0.55	1.2(22)	$kT = 2.0$	1.7(–11)	1.1(35)
	S source	0.80	1.2(22)	$kT = 2.0$	2.5(–11)	1.6(35)
IPC	Diffuse from rest of remnant	0.53	1.2(22)	$kT = 1.0$	1.3(–11)	2.0(35)
IPC	total SNR	2.45	1.2(22)	...	7.7(–11)	6.2(35)

^aFlux at the detector. Must be corrected for interstellar absorption to derive L_x .
^bDistance is 4.2 kpc.
^cIncludes some diffuse emission.

bright, small-diameter sources are “overexposed” and consequently not represented at their true prominence. There is strong diffuse emission extending NW–SE connecting and surrounding the two sources. The size, shape, and intensity distribution of the diffuse X-ray image correlate generally with the radio contours of the 1415 MHz radio map by Caswell, Milne, and Wellington (1981) shown in Figure 4c.

Table 1 lists the locations of the various sources derived from the X-ray images. The location of the source 4U 1510–59 agrees with the position of source S, as indicated in Figure 4d.

Table 2 lists fluxes and luminosities of the X-ray components of the SNR. IPC pulse height spectra (from a region $\sim 4'$ in diameter) were fitted with various spectral models to derive parameters. Although these are listed as characterizing the small, bright sources, a large region of diffuse emission is also included and represents an unavoidable contamination. The spectral resolution of the IPC is low, and parameters cannot be derived with great accuracy; nevertheless, the interstellar column density for all features of the remnant is measured as $N_H \sim 1 \times 10^{22}$ atoms cm^{–2} with an uncertainty of a factor of 2. The 2–10 keV *Ariel 5* spectrum of 4U

1510–59 by Chiappetti and Bell-Burnell (1982) is probably due to photons from only source S and its immediate surrounding nebula, since S and 4U 1510–59 are coincident and since the IPC indicates a softer spectrum for other components of the remnant. The *Ariel 5* data for S can be fitted almost equally well by thermal or power law spectra (the latter slightly preferred) with $N_H = 2\text{--}3 \times 10^{22}$ (Chiappetti 1981). We have derived a photon power law with index 1.7 from the *Ariel 5* spectrum and adopt this as the spectrum of source S. Once this index is fixed, the IPC observations determine a column density of $N_H = 1.2 \times 10^{22}$. Fixing this for the other features of the remnant allows us to determine temperatures or power law indices to an accuracy of $\sim \pm 30\%$.

Spectra of sources N and S have also been obtained with a 6' diameter field of view using the SSS instrument on the *Einstein Observatory*. The spectrum of source S and surrounding diffuse emission is compatible with an $\alpha = 1.7$ photon power law and that of source N with a thermal spectrum with $kT \sim 1$ keV (Szymkowiak 1982).

The flux from the small diameter NE source is ~ 0.1 the *Copernicus* upper limit from this region (Zarnecki *et al.* 1975).

The interstellar column density to these objects provides useful constraints on their location. In the direction to $l^{\text{II}} = 320^\circ$ the interstellar absorption A_v rises to 3.4 mag at the first spiral arm at 1.5 kpc, and remains at 3.4 mag until the next spiral arm at 4.2 kpc (Muzzio 1979; Georgelin and Lortet 1982). Since interstellar absorption and interstellar hydrogen column density N_{H} are correlated by $A_v = (4.5 \pm 0.3) \times 10^{-22} N_{\text{H}}$ (Gorenstein 1975; Ryter, Cesarsky, and Audouze 1975), the column density to X-ray objects between 1.5 and 4.2 kpc distant would be $N_{\text{H}} = 0.7 \times 10^{22} \text{ cm}^{-2}$. A column density of $N_{\text{H}} = 1.2 \times 10^{22} \text{ cm}^{-2}$ is correlated with $A_v = 5.5$ mag and would be found in objects at $l^{\text{II}} = 320^\circ$ lying between 4.2 kpc and the next spiral arm, which is at about 8 kpc.

There is consistency between the neutral hydrogen column density to the X-ray objects N and S and the SNR in general, and the H I kinematic distance of the nonthermal radio source associated with RCW 89. We show later that the interstellar absorption to RCW 89 is 5.5 mag, also consistent with these data.

The spectrum of source E does not show the strong absorption characteristic of other portions of the SNR. We deduce that it is a foreground object (distance ≤ 1.5 kpc), possibly a star. An optical candidate has not yet been identified.

III. OPTICAL AND INFRARED OBSERVATIONS

a) MSH 15—52

Figure 4a reproduces the area of MSH 15—52 from a 90 min *R*-band (6100–7200 Å) plate by the UK Schmidt telescope. The plate shows the circular patch of filamentary nebulosity which is RCW 89. Appearing on the plate is a newly discovered filament 9' NE of RCW 89; it falls within the radio source G320.5–1.0 (Shaver and Goss 1970), i.e., the extension of the radio arc eastward of the bright radio source identified with RCW 89. The filament has the same appearance as the RCW 89 filaments.

Thus, the whole of the NW arc including RCW 89 is a single entity and, by extension, RCW 89 is the brightest part of MSH 15—52, and, as argued by Clark and Caswell (1976), not a separate SNR. Figure 5 (Plate 1) shows contours of constant X-ray surface brightness overlaid on the *R*-band plate.

b) Source N

At the position of the source *N* on the ESO *B* sky atlas (bandpass 3800–4900 Å) no object is visible, but on the SRC *J* atlas (3950–5500 Å) there is a faint starlike object. In the atlas of supernova remnants by van den Bergh, Marscher, and Terzian (1973), a broad-band red picture shows a bright object within RCW 89 ($x = 59.5$ mm, $y = 77.5$ mm relative to the

lower left-hand corner of plate 14) at the position of the NE X-ray source.

Two images were obtained by J. Wall, P. Jorden, D. Thorne, and R. Gilmozzi (RGO) at the prime focus of the 3.9 m Anglo Australian Telescope (AAT) with a CCD camera built at the Royal Greenwich Observatory (Jorden *et al.* 1982). Figure 6a shows the *R*-bandpass picture (6100–7200 Å); the source appears as a starlike condensation embedded in a halo of nebulosity. Overall the object has a diameter of 4''.2 FWHM. The *I*-bandpass picture (not shown here) (7250–7600 Å) reveals a weak image.

Spectra were obtained at the AAT by David Hanes and Mark Phillips (AAO) with the Image Photon Counting System (~ 5 Å resolution). The spectrograph was set at P.A. = 145° , with the knot in the center of a 150'' long slit. Nebular emission is visible along the entire slit length, with a bright knot of nebulosity coinciding with the NE X-ray source. The spectrum of the bright knot was obtained by subtracting the flanking "sky" spectrum from the central 10'' of the spectrum of the knot. This spectrum is given in Table 3. It is the spectrum of a reddened ($A_v \sim 5.5$ from Balmer decrement), high-density ($n_e \sim 5 \times 10^3 \text{ cm}^{-3}$ from [S II] ratio), collisionally excited ([S II]/H α = 1.00) nebula, typical of a supernova remnant at ~ 5 kpc. The distribution of spectral lines accounts for the brightness of the optical image in the *B*, *J*, H α , *R*, and *I* images. The spectrum showed no detectable continuum. The stronger lines are repeated in similar ratios in the spectrum of the weaker nebulosity of RCW 89, 45'' NW of the knot, except that the [S II] ratio shows a value consistent with the low-density limit ($n_e \sim 10^2 \text{ cm}^{-3}$).

Observations of the knot in MSH 15—52 were made by G. Gilmore and N. Reid (ROE), R. Ellis (Durham), and D. A. Allen (AAO) at the infrared wavelengths of *J* (1.20 μm), *H* (1.64 μm), and *K* (2.19 μm), over the period 1981 September 11–12, using the infrared photometer-spectrometer (IRPS) on the AAT. The infrared observations have been interpreted by D. A. Allen as follows. With a 7'' focal-plane aperture and a 10'' N–S chop, contamination by nearby stars appeared to be no more than a few hundredths of a magnitude, and the photometry yielded:

$$J = 13.88 \pm 0.02 \text{ mag},$$

$$H = 13.13 \pm 0.02 \text{ mag},$$

$$K = 13.83 \pm 0.04 \text{ mag}.$$

These colors are quite unlike those of continuum sources; in particular the *H*–*K* value of -0.70 mag cannot be matched by any blackbody-like object. A suspicion that emission lines must be contaminating the magnitudes was confirmed by a spectrum covering the *H* window, taken with the same instrument at a resolving power of 50, on September 12. A strong emis-

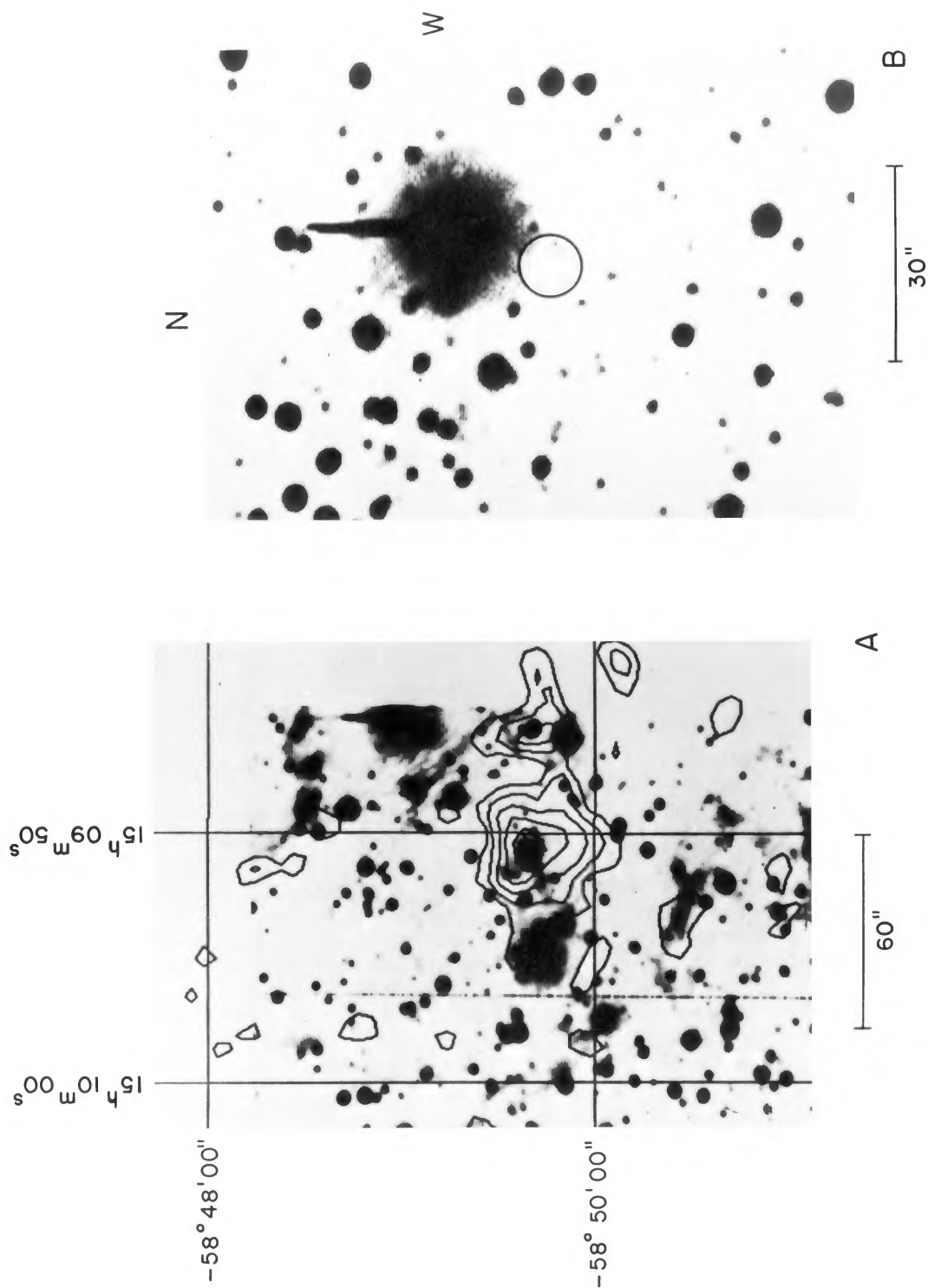


FIG. 6.—(a) Contours of constant X-ray surface brightness from HRI for source N overlaid on R-band picture. Data have been smoothed with a 5" Gaussian filter. The fringing around the bright star is instrumental. (b) Error circle for source S overlaid on R-band picture 6100–7200 Å. The spike pointing N from the bright star is an artifact of the CCD detector.

TABLE 3
LINE IDENTIFICATIONS IN MSH 15—52

$\lambda(\text{\AA})$	ID	Intensity ($H\beta = 100$)
3727	[O II]	96
4340	H γ	16
4475	[Fe II]	11?
4861	H β	100
4959	[O III]	61
5007	[O III]	175
5159	[Fe II]	15
5273	[Fe II]	5?
5412-3	[Fe II]	26
5890	[Na I]	73
6300	[O I]	364
6364	[O I]	116
6548	[N II]	594
6563	H α	1304
6583	[N II]	2152
6716	[S II]	513
6730	[S II]	795
7155	[Fe II]	360
7219	[Ca II]	356
7314	[Ca II]	...
7319	[O II]	1018
7329	[O II]	...
7378	[Ni II]	295
7452	[Fe II]	109

NOTE.— $F(H\alpha) = 3.2 \times 10^{-14}$ ergs $\text{cm}^{-2} \text{s}^{-1}$ observed from the knot; multiply by ~ 4 to correct for parts of the knot outside the spectrograph slit.

sion line was detected, together with some weaker satellite lines.

The strong line at $1.64 \mu\text{m}$ has been seen in M82 (Rieke *et al.* 1980), NGC 4151, and MWC 922 (Rieke and Lebofsky 1981). Here it has the largest equivalent width of any infrared line ever reported ($\sim 3000 \text{\AA}$), and its dereddened intensity of $1.9 \pm 0.6 \times 10^{-12}$ ergs $\text{s}^{-1} \text{cm}^{-2}$ measured in a $5''$ aperture is comparable with that of H β . A similar spectrum in the K atmo-

spheric window showed no strong lines; Brackett- γ was not seen. Further spectra in the H window were taken on September 13 by D. A. Allen (AAO). These spectra (Fig. 7) used a fully sampled resolution of 100. In all, five emission lines are recorded, as listed in Table 4. All can be attributed to [Fe II] transitions among low-lying states which must be collisionally excited since they are much stronger than the transitions from higher levels. Some contribution from [Si I] $^3P-^1D$ ($1.607 \mu\text{m}$, $1.645 \mu\text{m}$) cannot be excluded, but the low ionization potential of neutral silicon makes this unlikely.

It has been pointed out by Storey (1982) that if the temperature in the knot is lower than about $3 \times 10^4 \text{ K}$, the possibility that the a^4F-a^4D [Fe II] lines are excited via cascading from higher odd-parity quartets can be ignored. The line intensities can then be calculated from the data in Nussbaumer and Storey (1980). With increasing electron density the levels of a^6D become populated, and this introduces density sensitivity into some of the line ratios; at 10^4 K the ratio of the emissivities of the lines at $1.644 \mu\text{m}$ and $1.602 \mu\text{m}$ is ~ 40 at $n_e = 10^2 \text{ cm}^{-3}$ and ~ 3 at $n_e = 10^6 \text{ cm}^{-3}$. The density sensitivity of this line ratio is given in the inset of Figure 7 (Storey 1982). The observed ratio in this object of 4.4 ± 0.8 occurs according to these calculations at a density of $5 \times 10^4 \text{ cm}^{-3}$. The high density indicated by the data is confirmed by the optical spectrum and the ratio of the sulphur lines, which arise from an ion of similar ionization potential to Fe II and thus from the same region. According to Rieke and Lebofsky (1981), the $1.64 \mu\text{m}$ [Fe II] line is seen in the star MWC 922 where it is accompanied by a line at $1.26 \mu\text{m}$ of comparable strength. We have no spectral data within the J window, where that line lies, but the broad-band flux which we see there could be contributed by emission lines of similar total intensity to those in the H window. The K window, on the other hand, contains no strong emission lines and must therefore include a continuum source ~ 14 mag. A continuum also underlies the H window, at ~ 14.5 mag.

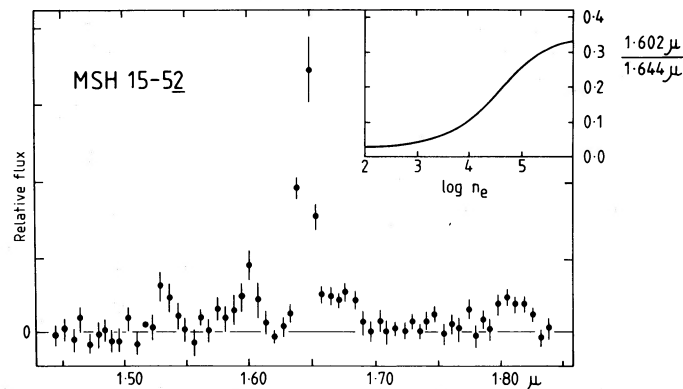


FIG. 7.—Infrared spectrum around $1.6 \mu\text{m}$ of the bright knot identified with N. Inset: density dependence of $1.602/1.644 \mu\text{m}$ line ratio.

TABLE 4
INFRARED EMISSION LINES IN MSH 15-52

Measured Wavelength (μm)	Fe II Identification	$\lambda(\mu\text{m})^a$	A-Value ^b (in 10^{-4} s^{-1})	Relative Flux
1.53	$a^4F_{9/2}-a^4D_{5/2}$	1.53389	10	15
1.597	$a^4F_{7/2}-a^4D_{3/2}$	1.59991	14	23
1.641	$a^4F_{9/2}-a^4D_{7/2}$	1.64400	19	100
1.668	$a^4F_{5/2}-a^4D_{1/2}$	1.66422	16	19
	$a^4F_{7/2}-a^4D_{5/2}$	1.67733	8	
1.81	$a^4F_{3/2}-a^4D_{3/2}$	1.79759	7	20
	$a^4F_{5/2}-a^4D_{5/2}$	1.80051	6	
	$a^4F_{7/2}-a^4D_{7/2}$	1.80989	4	
	$a^4D_{7/2}-a^4P_{5/2}$	1.812	5	
	$a^4D_{5/2}-a^4P_{1/2}$	1.814	8	
Also predicted, but not convincingly seen:				
	$a^4F_{5/2}-a^4D_{3/2}$	1.71159	4	
	$a^4F_{3/2}-a^4D_{1/2}$	1.74541	8	
	$a^4D_{7/2}-a^4P_{3/2}$	1.749	6	

^aJohansson 1978.
^bNussbaumer and Storey 1980.

The continuum is too blue to be readily attributed to thermal emission from dust. In particular, the continuum within the $2\mu\text{m}$ window itself is quite blue, with a strong suggestion of a break at the wavelength of the hydrogen Pfund discontinuity. This indicates that free-free and free-bound emission from hydrogen may be responsible for the H and K band continuum. Using the data in Osterbrock (1974) and Sibille, Lunel, and Bergeat (1974), assuming the gas to be in case B equilibrium at 10^4 K , and taking the reddening at K to be 0.4 mag, we predict from the K continuum an $H\beta$ flux in a $7''$ aperture of $3.8\times 10^{-12}\text{ ergs s}^{-1}\text{ cm}^{-2}$. This may be compared with the dereddened flux in a $1''\times 10''$ slit centered on the knot of $9\times 10^{-13}\text{ ergs s}^{-1}\text{ cm}^{-2}$ (Table 3). We estimate that this optical spectroscopic observation of $H\beta$ recorded ~ 0.3 of the total line flux, consistent with the $1''$ slit width of this observation over the $4''$ diameter object. Within the likely errors, therefore, the two values agree, and we conclude that there is no extra continuum source brighter than about $K=15$, or $V=19$ for a hot star suffering 5.5 mag reddening. This is consistent with the observed lack of optical continuum $V>19$, $I>18$ seen in the optical spectrum and infrared CCD image described earlier.

We note that this is the first time that the infrared lines from [Fe II] have been seen in a supernova remnant and that in total these lines are of intensity comparable to Balmer emission. They are thus a significant cooling mechanism in this SNR.

c) Source S (4U 1510-59)

Images of the field of the source S were obtained at the prime focus of the AAT with the RGO CCD camera (Jorden *et al.* 1982). Figure 6*b* shows the R (6100-7200

$\text{\AA}$) image and the HRI error circle. The HRI position is $18''$ S of a 12th magnitude star (brightest star in Fig. 6*b*) which is star 35 of Orsatti and Muzzio (1979), the same star as star 10 of Muzzio (1979). Data on this star are given in Table 5. Although it shows mass loss characteristics and has interstellar absorption consistent with the X-ray spectrum of the source S, its position is well outside the error box. Furthermore, by comparison with other O stars observed with the IPC (Harnden *et al.* 1979*a*; Seward and Chlebowsky 1982) its expected counting rate is only $\sim 0.006\text{ s}^{-1}$, compared to the 0.3 s^{-1} observed from source S.

Two faint stars ($R\sim 22$) are within the HRI error circle. Four other stars lie just outside its boundary (brightest is $R\sim 20$). These stars do not show on the SRC J Southern Sky Survey ($B<23$) but show more clearly on an I -band CCD image. They are presumably reddened by the interstellar absorption. The two inner stars are candidates for the optical identification of 4U 1510-59.

TABLE 5
STAR 10 = 35 [$\alpha=15^{\text{h}}09^{\text{m}}58^{\text{s}}.6$, $\delta=-58^{\circ}56'40''$ (1950)]

Data	Reference
$V=12.48$, $B-V=1.66$	Orsatti and Muzzio 1979
$V=12.43$, $B-V=1.35$	Bessell 1982
$V=11.63$ (?), $B-V=0.58$ (?) ...	Muzzio 1979
Spectral type O6.5 III((f))	^a
$A=5.0$ to 5.9 , $M=-5.5$	$d=2.5$ to 3.9 kpc

^aAAT spectrum classified by P. W. Hill (St. Andrews) according to the schemes of Conti and Alschuler 1971 and Walborn 1971.

IV. DISCUSSION

a) The Remnant MSH 15—52

The properties of the remnant overall can be roughly derived from the X-ray surface brightness of the limb. We assume: a shell of thickness $1/10$ the radius (which, based on both radio and X-ray maps, is 18 pc), a swept-up mass much greater than the ejected mass, cosmic abundances, ion-electron equilibrium, and the Sedov model (Culhane 1977) to describe the blast wave. The X-ray surface brightness and luminosity of the eastern side are low. The implied electron density is only $\sim 0.2 \text{ cm}^{-3}$ (0.05 cm^{-3} in ISM), giving an amount of X-ray emitting material of $\sim 45 M_{\odot}$ integrated around the entire (assumed) rim. If a brighter region on the W rim (just W of source N) is used, these numbers become $\sim 0.5 \text{ cm}^{-3}$ and $100 M_{\odot}$. The X-ray temperature is comparatively high, implying relative youth, although the observed morphology is more like that of an old remnant. We suspect that there is strong, soft, X-ray emission (such as is observed from the Cygnus Loop or Vela X) which is not seen because of interstellar absorption, and that only a fraction of the heated material associated with the blast wave is observable. Using a diameter of $30'$ (from the radio data) and the empirical age-diameter relationship of Clark and Caswell (1976) gives an age estimate of 10^4 years. Alternatively, we can use the Sedov relationship assuming an initial energy release, E_0 , of 10^{51} ergs and interstellar density, n_0 , of 1 atom cm^{-3} , giving the age of the remnant $\sim 2.1 \times 10^4$ years. Since age varies as $(n_0/E_0)^{1/2}$, decreasing n_0 to 0.1 gives an age estimate of 6700 years by this technique.

The appearance of the SNR is dominated by the bright X-ray, radio, and optical regions on the NW side of the remnant, the side nearer to the higher density galactic plane region (Caswell, Milne, and Wellington 1981). The overall structure is not atypical of SNRs and is very reminiscent of RCW 86 in which a bright circular patch of filamentary nebulosity (van den Bergh, Marscher, and Terzian 1973) is superposed on a radio-bright area on the rim of a circular shell (G315.4—2.3) consisting of two bright arcs (Caswell, Clark, and Crawford 1975). A proposed explanation (Dopita 1982) for the asymmetry of such remnants is that the supernova explosion which created it occurred in a region of interstellar medium with a gradient of density increasing dramatically toward the galactic plane. According to the same idea, the shock in MSH 15—52 might have propagated rapidly away from the galactic plane into a region of density $\sim 0.1 \text{ cm}^{-3}$ to produce the SE arc, but more slowly to the NW, a region of higher density with clouds having $n = 10^2\text{--}10^3 \text{ cm}^{-3}$. This produced the brighter NW radio arc, the optical nebulosity RCW 89, and the X-ray bright area $\sim 10'$ in extent, containing the source N.

b) Source N

Although the HRI is unable to detect the surrounding broad, diffuse emission above background, it resolves the pointlike source N into two components. These two knots of emission are aligned east-west and separated by $36''$. The stronger component, the easterly source, appears extended in the HRI, with diameter $\sim 10''$. From Figure 6a, it can be seen that the easterly intense component of N coincides with the bright knot of H α emission identified in § III. From its optical spectrum and reddening it is clear that the knot is part of RCW 89. Using the observed X-ray diameter of $10''$ and luminosity of $2 \times 10^{34} \text{ ergs s}^{-1}$ and assuming cosmic abundances, equilibrium, and $T \approx 10^7 \text{ K}$, we calculate a density of $\sim 100 \text{ cm}^{-3}$. The optical spectra require $T \approx 10^4 \text{ K}$ and $n \approx 5 \times 10^3 \text{ cm}^{-3}$. The luminosity in optical lines is $\sim 1.4 \times 10^{35} \text{ ergs s}^{-1}$. The IR spectrum, assuming $T = 10^4 \text{ K}$, requires $n \approx 5 \times 10^4 \text{ cm}^{-3}$ and an IR luminosity of $4 \times 10^{34} \text{ ergs s}^{-1}$. In view of the uncertainties in the assumed temperatures, the lack of pressure equilibrium is probably not significant.

The picture that emerges from these data is of a dense cool knot with a hot shock-induced evaporated halo (McKee and Cowie 1975). However, it must be noted that source N is on the rim of the remnant MSH 15—52, and an X-ray knot this bright on the rim of an older remnant is unprecedented except perhaps in the case of Pup A and the bright UV knots in Vela (Danziger, Wood, and Clark 1980).

c) Comparison with Knots in Puppis A

The old SNR Puppis A has been mapped with the Einstein HRI (Petre *et al.* 1982). Although the shell is irregular, the measured diameter of Pup A is $\sim 50'$ and the center is $\sim 3.5^\circ$ from the galactic equator. Since the distance is thought to be 2 kpc, Pup A has approximately the same linear dimensions and is approximately the same distance from the galactic plane as MSH 15—52. Thus, the two remnants might be considered to be at approximately the same age and evolutionary condition.

The HRI image of Puppis A shows two bright regions at the limb of the remnant which Petre *et al.* explain as the interaction of the blast wave with clouds in the ISM. The East bright cloud of Pup A has an area of 8 arcmin^2 and the North cloud an area of 2 arcmin^2 . Derived electron densities are, on the average, $10\text{--}20 \text{ cm}^{-3}$. Both clouds are larger and less dense than source NE of MSH 15—52. There is, however, a bright spot in the North cloud with dimensions $8''$ by $20''$, and the calculated electron density is 100 cm^{-3} , the same as that calculated for the NE knot of MSH 15—52.

There is an important difference, however, between Pup A and MSH 15—52. Puppis A is closer, absorption in the ISM is less, and X-rays from low-temperature

regions can be seen which are unobservable in MSH 15–52. Zarnecki *et al.* (1978) have resolved the X-ray spectrum of Pup A into two thermal components characterized by temperatures of 2.5×10^6 K and 1.2×10^7 K. Emission from the East cloud of Pup A has been observed with the *Einstein* FPCS by Winkler *et al.* (1981) and found to originate from a low-temperature region. If we imagine Pup A moved twice as far away, much of the observed X-ray emission would be absorbed and the apparent X-ray brightness diminished from that observed by Petre *et al.*

Since any soft component of emission from MSH 15–52 is unobservable, the densities calculated are lower limits and, even though Pup A shows a similar phenomenon, there may still be a problem with the energy required in a spherical blast wave to excite the bright spot on the rim of MSH 15–52. The thermal energy of the knot and the solid angle subtended require an energy in excess of 2×10^{51} ergs. Such a large energy does have the advantage of reducing the “Sedov” age to a value approaching the pulsar characteristic age.

There are several acceptable possibilities which might explain the high brightness at the NE knot: (1) we are viewing a filament end-on. Extending the length of the filament to increase the volume a factor of 10 reduces the blast wave energy required a factor of 3. (2) We might invoke a nonequilibrium situation or an enrichment of metallic elements in the knot so that the emissivity of the plasma is increased. This would seem to be a perfectly acceptable explanation, especially if the knot is circumstellar ejecta from the supernova precursor. Abundance anomalies in the dense knots of Pup A are well documented. (3) Energy from the supernova explosion was favorably directed toward the N source as a jet of material, or an interstellar “bullet”—a less plausible explanation. (4) The supernova explosion occurred closer to source N than the present position of the pulsar. (5) Energy from the pulsar is directed toward RCW 89. This would explain the bright ridge of diffuse emission surrounding both source S and source N. (6) There is a nearby, otherwise undetected, compact object which excites the knot.

d) Source S

Source S must be a neutron star rotating with a period of 0.150 s. It is gratifying to find such an object within the shell of a SNR, but this particular pulsar presents somewhat of a dilemma. The characteristic age of 1600 years is not compatible with our conception of MSH 15–52 as a remnant which may be of age $\sim 10^4$ years.

The object has been shown by Manchester, Tuohy, and D’Amico (1982) to be a radio pulsar, and the identification as a young object is strengthened by the observation of an X-ray halo with extent $5' - 10'$ and $L_x \sim 10^{35}$ ergs s^{-1} surrounding the source. Although the

IPC spectra cannot exclude thermal radiation, the rotational energy loss of the pulsar is more than adequate to power a synchrotron source with these characteristics. This halo is $\sim 3 \times 10^{-3}$ as luminous as that associated with the Crab pulsar (Toor, Palmieri, and Seward 1976) and 10^2 more luminous than the small diffuse halo observed by *Einstein* around the Vela pulsar (Harnden *et al.* 1979b). This diffuse emission, since it was undetected by the HRI, contains no bright knots or condensations and is thus compatible with a synchrotron source. The optical counterpart of the Vela pulsar is $M \sim 24.2$ (Manchester *et al.* 1978). The pulsar in MSH 15–52 is more distant and more heavily absorbed than the Vela pulsar and therefore, by these arguments, much fainter. On the other hand, any optical candidate could be brighter than the Vela pulsar if the ratio of X-ray to optical pulsations is constant in pulsars. The stars visible on the CCD images must be regarded as possible candidates.

e) MSH 15–52 as a Young Remnant

If the supernova were unusually energetic with $E_0 = 10^{52}$ ergs and a low n_0 (0.1 cm^{-3}), the age calculated from the Sedov model would be only 2100 years, close to the “age” of the pulsar (1600 years). If the remnant is young, the observed size of the shell requires large E_0 and low n_0 . The observed low surface brightness of the shell is also a consequence of the low density. The large energy release, however, requires a shock velocity of $\sim 3000 \text{ km s}^{-1}$ and predicts a temperature of $\sim 10^8$ K in the heated material behind the shock, a factor of 10 higher than observed. Young supernova remnants with high-velocity shocks do emit high energy X-rays implying material at high temperature (Pravdo and Smith 1979); however, the average electron temperature of the bulk of the material is considerably less than that predicted by the Sedov model.

If E_0 were abnormally high, there should be high-energy X-ray emission from MSH 15–52 extending to 20–30 keV. Indeed, Chiappetti and Bell-Burnell (1982) have observed a relatively hard spectrum below 10 keV which is confirmed by the *Einstein* MPC. The IPC, however, shows that the hard X-rays come from the pulsar and its surrounding nebula, not from the rim of the SNR. It would be interesting to see spectra from other satellites such as *HEAO 1*, which was capable of resolving K X-rays from Fe. This might be a definitive test of the existence of a high-temperature plasma. If E_0 were $\sim 10^{52}$ ergs, there would be no problem exciting the bright knot, but since the ISM density is probably higher along the northwest rim, we would expect this portion of the remnant to be much brighter than is observed. In this regard, it is interesting to point out that the remnant of SN 1006 has a rather low X-ray luminosity of $\sim 3 \times 10^{35}$ ergs s^{-1} , and the temperature of the shell, which is observed clearly because interstel-

lar absorption is low, is also less than predicted by the Sedov model (Pye *et al.* 1980).

One possible way around the problems highlighted above could be to invoke a more readily acceptable $E_0 \sim 10^{51}$ ergs plus a very low density ambient ISM, say $n_0 \sim 0.01$, arising from a previous supernova explosion (an interstellar tunnel) or the hot wind of a massive precursor (a bubble). The shock from the recent supernova explosion expanding in this tenuous medium is underluminous except where it has encountered the dense knot on the NW rim.

f) MSH 15–52 as an Old Remnant

Suppose the pulsar is not young, and the “characteristic age” of the pulsar is not a good measure of the pulsar’s true age. There is after all only one object, the Crab pulsar, for which the known age can be accurately compared with the characteristic age. Perhaps some pulsars are born with a weak magnetic dipole moment that takes a long time to build up to the point where the dipole radiation exerts the strong torque which causes the pulsar spin-down.

If MSH 15–52 is an “old” remnant, we can now accept that $E_0 \approx 10^{51}$ ergs, $0.1 < n_0 < 1.0 \text{ cm}^{-3}$, and MSH 15–52 is similar to Vela X and Puppis A. Most of the emission from the shell is soft and completely absorbed in intervening interstellar material. We are only able to trace the existence of the shell through radio observations and through a small amount of high-energy X-ray emission from the heated material behind the shock. Our previous discussion of a supernova explosion in a stratified ISM can now be invoked as a satisfactory explanation of the properties of MSH 15–52. However, there seem to be more problems in accepting MSH 15–52 as an “old” remnant than as a “young” remnant—especially the fact that the knot and indeed the entire RCW 89 region is abnormally bright for an “old” remnant.

g) Two Compact Objects?

There is a striking similarity between the characteristics of RCW 89 (the radio-bright region filled with optical filaments NW of the pulsar) and those of other filled-center supernova remnants, particularly the radio emission which increases steadily from the edge of the region to a maximum coinciding exactly with the position of the bright knot. For example, 3C 58 (Becker, Helfand, and Szymkowiak 1982) is a diffuse X-ray source of diameter $\sim 5'$ with both radio and X-ray emission maximum at the center. There is a weak pointlike X-ray source at the center, and the IPC counting rate, $0.3 \text{ counts s}^{-1}$, is close to the $0.6 \text{ counts s}^{-1}$ we observe from RCW 89. The SNR 3C 58 also contains optical filaments, although not as bright as those in RCW 89.

Perhaps the strong excitation of the N source complex and the surrounding bright diffuse emission indicates the existence of an underlying compact object not prominent itself in X-rays because of an unfavorable orientation of the rotation axis.

There are a number of ways in which a SNR containing two young neutron stars could be made. First, both compact objects could be created in the same supernova event. Conservation of energy and angular momentum allow the production of multiple neutron stars in the gravitational collapse of the core of a single massive star. In this case, the two compact objects would be separated by 7.5 and, given the distance of 4 kpc and age of $20,000$ years, the separation velocity is at least 400 km s^{-1} , high but not out of the question.

Alternatively, there could be two supernovae from two stars, perhaps originally in the same multiple-star system and disrupted by one of the explosions. Since the age of MSH 15–52 is small compared to the time required for a massive star to evolve to the point of gravitational collapse, this requires the two progenitor stars to be virtually identical, a rather unlikely occurrence.

Equally unlikely would be two virtually identical separate stars, members of a small association, both exploding within $\sim 2 \times 10^4$ years and resulting in two accidentally superposed SNRs.

Without a direct observation of a neutron star within RCW 89, the hypothesis that this region is shock-heated material in the rim of MSH 15–52 is the more plausible explanation.

V. CONCLUSIONS

MSH 15–52 has a shell characteristic of a middle aged SNR, but the central pulsar and a bright region on the rim indicate a younger system. We have discussed several possibilities for the origin of this fascinating remnant, none of which are completely consistent with the observations, although the possibility that the system is young ($< 2000 \text{ yr}$) and was produced in a particularly energetic outburst ($E_0 \sim 10^{52}$ ergs) raises fewest objections. However, the pulsar may be older than its apparent characteristic age, thus allowing a more modest initial energy for the supernova that produced the system. Future observations and/or inspection of data already in hand should give a measure of the behavior of P and $\dot{P}$ with time and a flux or upper limit to high-energy radiation from the rim of the remnant. These should provide definitive answers to the ages of the pulsar and the remnant.

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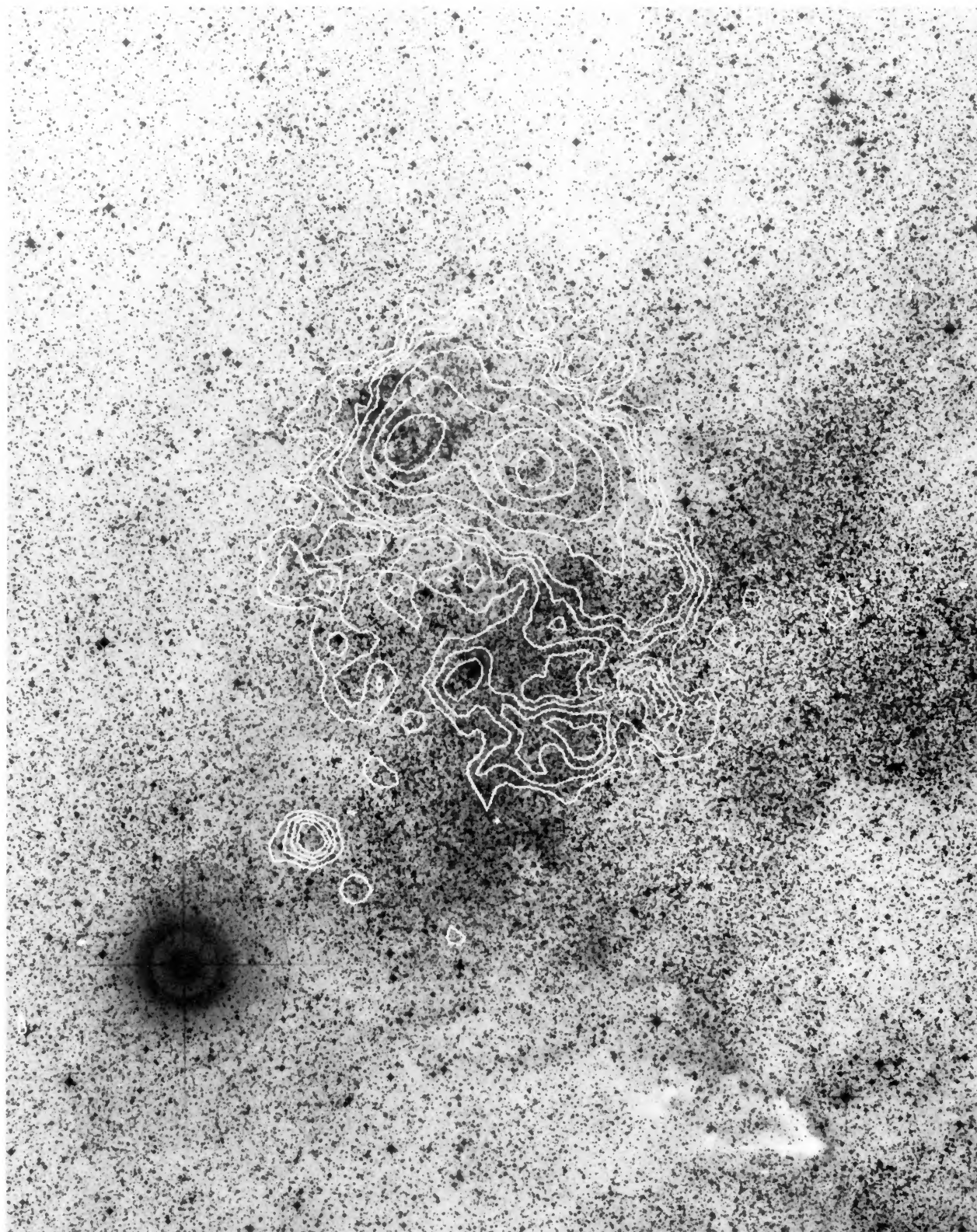


FIG. 5.—IPC contours overlaid on 90 min III a-F + R-band filter UK Schmidt Telescope picture
SEWARD *et al.* (see page 703)