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AN OPTICAL INVESTIGATION OF THE PECULIAR SUPERNOVA REMNANT CTB 80

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ABSTRACT

Interference-filter photographs and optical spectrophotometry are used to investigate the optical emission associated with the peculiar supernova remnant CTB 80. Optically, the remnant consists of outlying diffuse and filamentary emission surrounding a small, central ring of filaments which are coincident with the central radio emission peak. Spectra of two filaments in the southwestern part of the remnant show strong [S II] emission relative to Hα; in conjunction with the nonthermal radio emission in this region, this suggests that the filaments are shock heated. Filaments outside the radio structure in the northeast show a similar optical spectrum and may also be a part of CTB 80. The central filaments form a well-defined shell structure in the light of [O III] λ5007 but are irregular in Hα, showing both knots and diffuse emission. A spectrum of these filaments also shows strong [S II] relative to Hα, but the flat radio spectrum and low expansion velocity in this region make a shock-heated interpretation questionable. We consider the optical observations in relation to radio and X-ray data on CTB 80 and suggest an age of at least several thousand years for the remnant. We also discuss the possibility that the optical emission from the central region may be photoionized.

Subject headings: nebulae: individual — nebulae: supernova remnants

I. INTRODUCTION

At radio frequencies, supernova remnants (SNRs) have been classified into two main groups. The majority fall into the shell remnant category, showing a partial or complete ring of nonthermal radio emission ($\alpha \gtrsim 0.3$; $S_\nu \propto \nu^{-\alpha}$). A smaller number of SNRs are filled-center remnants, or Crab Nebula-like remnants after the best known member of the category (also called "plerions" or "plethoric" remnants; see Weiler 1978; Weiler and Panagia 1978, 1980; Shakeshaft 1979). These remnants show a centrally peaked radio brightness distribution, high polarization, and a flat spectral index ($\alpha \lesssim 0.3$). Crab-like SNRs are believed to be relatively young and sustained by relativistic particles from a central pulsar, although the pulsar is often not directly observed (cf. Weiler and Shaver 1978; Caswell 1979).

Recent X-ray and high-resolution radio results have shown that this classification scheme may be too simple. Several SNRs that appear to be composites of the two classifications have now been identified. These include G326.3−1.8 (Clark, Green, and Caswell 1975), G29.7−0.3 (Becker, Helfand, and Szymkowiak 1983), MSH 15−5(2) (Seward *et al.* 1983), and the Vela X SNR which shows an extended X-ray synchrotron nebula surrounding the Vela pulsar (Harnden *et al.* 1979; Weiler and Panagia 1980). CTB 80 may also be a member of this composite class, although some additional peculiarities make this classification uncertain.

The radio properties of CTB 80 have been discussed by Velusamy and Kundu (1974), Velusamy, Kundu, and Becker (1976), Strom, Angerhofer, and Velusamy (1980), and Angerhofer *et al.* (1981): a small diameter ($\lesssim 1'$) filled-center source with flat spectral index ($\alpha = 0.0$) is observed at the center of a region of very extended ($\sim 1°$) low surface brightness nonthermal emission ($\alpha \approx 0.8$). However, unlike other composite sources, the extended structure of CTB 80 does not appear to be a shell or partial shell of emission. Instead, a plateau of emission extends $\sim 10'$ eastward from the central core of radio emission with the outermost radio contours showing a unique, three-lobed structure. The high resolution Westerbork maps of Angerhofer *et al.* (1981) show that the spectral index and projected magnetic field change smoothly from the central region to the outer radio lobes of CTB 80.

Inspection of the Palomar Observatory Sky Survey (POSS) red print reveals a few faint knots of emission coincident with the central radio source. Deeper imagery in Hα and [S II] by Angerhofer, Wilson, and Mould (1980, hereafter AWM) shows that these knots are part of a faint, irregular ring of emission that is elongated in the east-west direction and that corresponds well to the central radio structure at 2695 MHz. Spectra of some of these central filaments show strong [N II] λ6584 and [S II] λλ6717, 6731 emission relative to Hα, with substantial variations in the relative line intensities.

Van den Bergh (1980) obtained Hα + [N II] and [S II] plates of this region with the Palomar 1.2 m Schmidt telescope. Because SNRs generally show much stronger [S II] emission relative to Hα than do H II regions, comparison of such plates usually allows SNR filaments to be identified. Van den Bergh's plates show faint filamentary emission extending from about

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10′ west of the core to the southwest (his "filament 1"), roughly along the radio lobe in this region, and some brighter filaments (his "filament 2") to the northeast well outside the known extent of CTB 80's radio emission. From the [S II] photograph, van den Bergh concluded that filament 2 was part of a SNR, although its relationship to CTB 80 was uncertain. Filament 1 was so faint in [S II] and Hα + [N II] that no conclusion could be drawn as to whether it was photoionized or shock heated.

Becker, Helfand, and Szymkowiak (1982) have reported X-ray data for the central region of CTB 80 obtained with the High Resolution Imaging detector (HRI) of the *Einstein Observatory* (see Giacconi *et al.* 1979). The HRI is not very sensitive to faint diffuse emission, but a centrally peaked, extended X-ray source was detected coincident with the central radio core. Their analysis indicates that a significant portion of this X-ray emission is due to a point source. However, the low count rate did not allow a significant search for pulsations to be made.

In this paper, we present optical data on this remnant including both image tube photography and spectroscopy. In particular, we discuss a deep photograph of the central region in the light of [O III] λ5007 which shows considerably different structure from that seen in Hα. Also, a wider field photograph centered on Hα + [N II] shows that there is considerable structure within the outlying optical emission that extends to the southwest from the core. Spectrophotometry of some of these outer filaments suggests that they are shock heated. In addition, we present a spectrum and an Hα + [N II] photograph of van den Bergh's (1980) filament 2 and discuss its possible relationship to CTB 80. The observations are presented in the following section and discussed in § III.

II. OBSERVATIONS

a) *Interference-Filter Photography*

We obtained three interference-filter photographs of CTB 80 as detailed in Table 1. The wide-field Hα + [N II] photographs shown in Figures 1*a* and 1*b* (Plates 7 and 8) were obtained with a 144 mm ITT image tube at the f/7.5 focus of the McGraw-Hill Observatory's 1.3 m telescope. This single-stage tube, on loan from Kitt Peak National Observatory (KPNO), has an extended S-20 photocathode, magnetic focusing, and a fiber optic output. The filter was centered at 6570 Å with a peak transmission of 56% and a full width at half-maximum of 75 Å. The images were recorded on nitrogen-sensitized IIa-D plates with original plate scale of 22″ mm^{-1}; the smallest features visible on these plates are of order 3″. The filamentary structure extending to the southwest from the core shows considerably more detail than was previously known. The filaments to the northeast appear more diffuse than the southwest filaments. The region around the core has been enlarged and is shown in Figure 2*a*.

An [O III] photograph was obtained with a Carnegie Image Tube (CIT) camera at the f/7.5 focus of the no. 1-91 cm telescope at KPNO. The filter was centered at 5009 Å (FWHM) and a peak transmission of 63%. The image was recorded on a baked IIIa-J plate at an original scale of 30″ mm^{-1}. Although the seeing and transparency were excellent during the exposure, the resolution was limited to 2″ by the system performance. The field of view was 17′ in diameter, but no [O III] emission was detected outside of the core region, which is shown enlarged in Figure 2*b*. In [O III], the core appears as a ring of emission which is brightest on the southwest side.

b) *Spectrophotometry*

Spectra of three outer filaments and one position in the core of CTB 80 have been obtained using three different telescopes and detectors, as listed in Table 2. The position called "SW" is about 9′ southwest of the core at $19^h50^m23^s.5$, $+32°42'26''.7$ (1950), and is indicated with an arrow in Figure 1*a*. This filament was referred to as the "wisp" by Angerhofer *et al.* (1981; see their Fig. 4). It was observed with the KPNO 2.1 m telescope and Intensified Image Dissector Scanner (IIDS) with the reduced data shown in Figure 3. This filament was also observed at higher resolution in the red using the 1.3 m telescope and 2000 channel intensified Reticon scanner (similar to the device described by Shectman and Hiltner 1976) at the McGraw-Hill Observatory. This spectrum, shown in Figure 4, shows the [N II] lines resolved from Hα and the [S II] λλ6717, 6731 lines clearly separated. The McGraw-Hill system was also used at a lower dispersion to observe a position in the central core on the southwest side of the ring visible in Figure 2 at $19^h51^m02^s.1$, $+32°44'51''.8$ (1950), and a filament near the tip of the southwest radio lobe at $19^h48^m50^s.9$, $+32°27'11''.6$ (1950; position SSW). Finally, the 1.5 m telescope at the Whipple Observatory on Mount Hopkins in Arizona was employed in conjunction with a photon counting Reticon detector (the "Z-machine"; see Latham 1982) to obtain the spectrum of a position in the filaments to the northeast, at $19^h54^m49^s.9$, $+33°12'40''.0$ (1950; see Fig. 1*b*). The Mount Hopkins system is not normally used for spectrophotometry, but relative line intensities for lines reasonably close in wavelength (e.g., [O III]/Hβ or [S II]/Hα) should be reliable.

All three systems are equipped with TV guiders which allowed accurate slit positioning. Night sky emission was subtracted and the spectra calibrated using observations of stars whose energy distributions are known (Oke 1974; Stone 1977). Although none of the nights was of photometric quality, the

TABLE 1

CTB 80 PHOTOGRAPHIC LOG

Date (UT)	Position	Telescope and Instrument	Filter	Field of View (arc min)	Exposure Time (min)
1981 Jul 26	Center	McGraw-Hill 1.3 m; 144 mm IT	Hα + [N II]	45	120
1981 Oct 5	Center	KPNO No. 1–91 cm; CIT	[O III]	17	90
1982 Aug 28 ...	NE	McGraw-Hill 1.3 m; 144 mm IT	Hα + [N II]	45	120

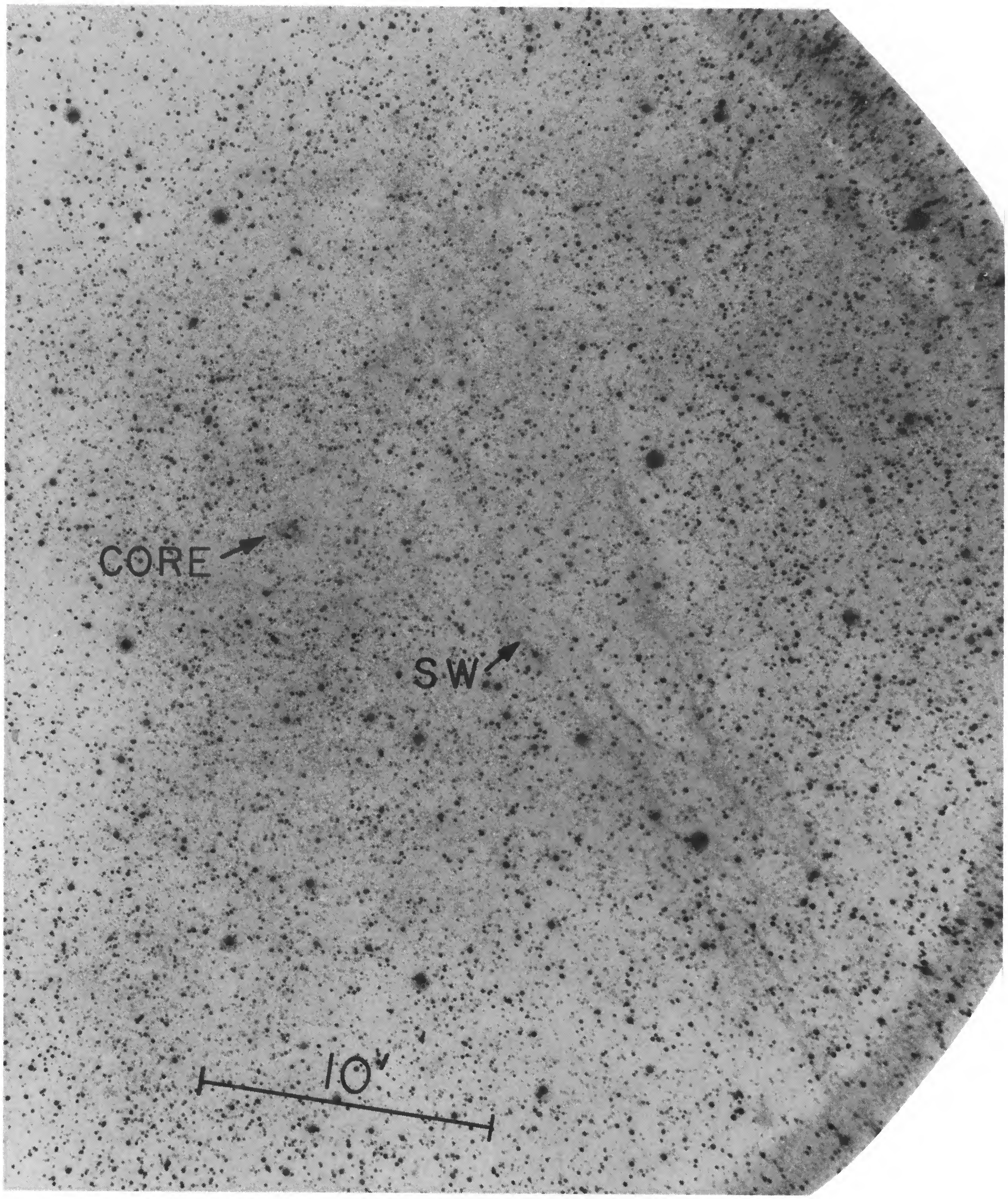

FIG. 1*a*.—An Hα + [N II] interference-filter photograph of the central and southwestern portions of CTB 80. In this and all of the photographs, north is up and east is to the left. (The scale marker is east-west.) An arrow indicates the position of the filament "SW" that was observed spectroscopically. The dark ring at the edge of the field is due to internal reflections.

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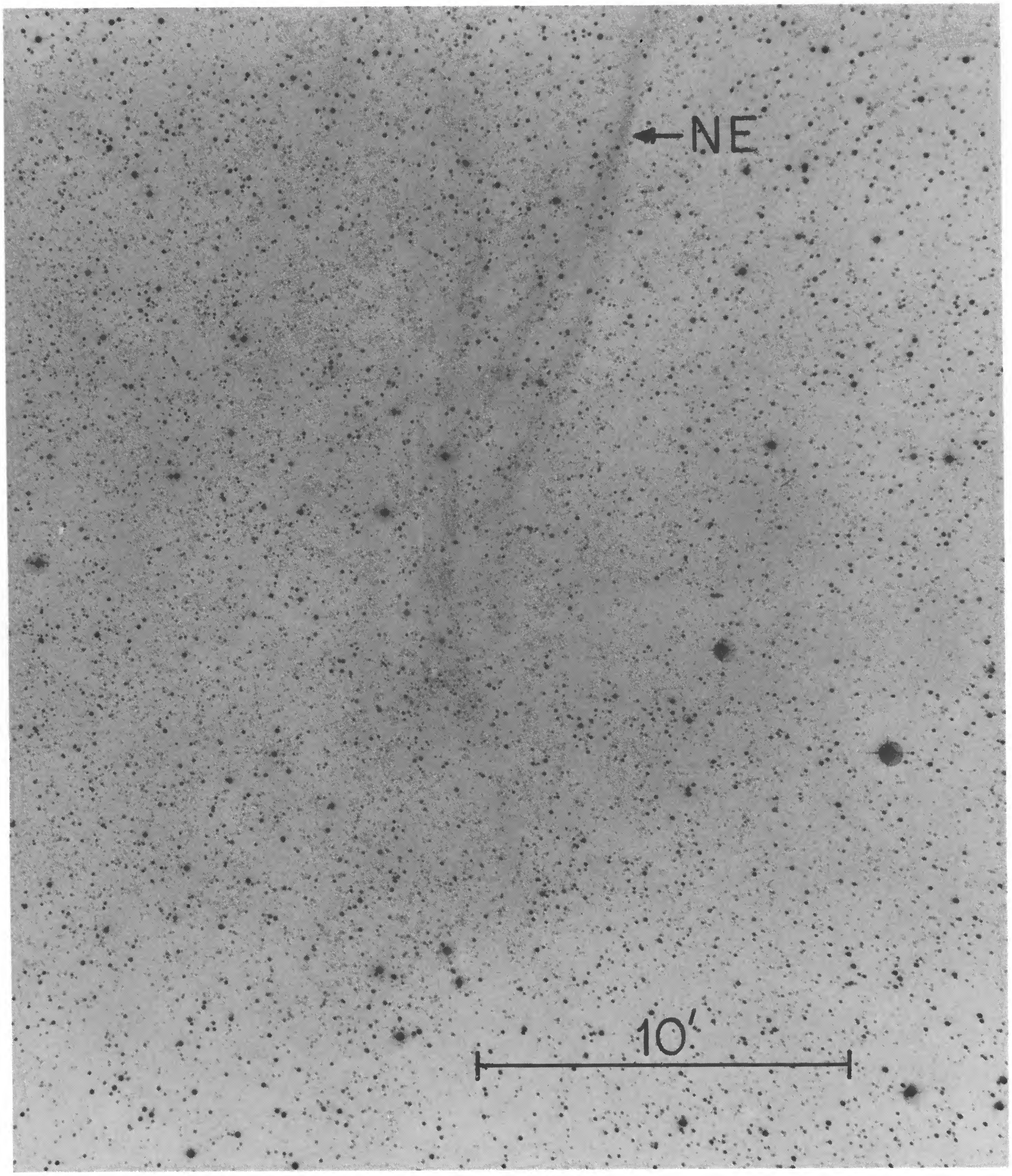

FIG. 1*b*.—An Hα + [N II] photograph of the northeast filaments near CTB 80 (van den Bergh's 1980 filament no. 2). An arrow marks the position observed spectroscopically. The scale is slightly different from Fig. 1*a*.

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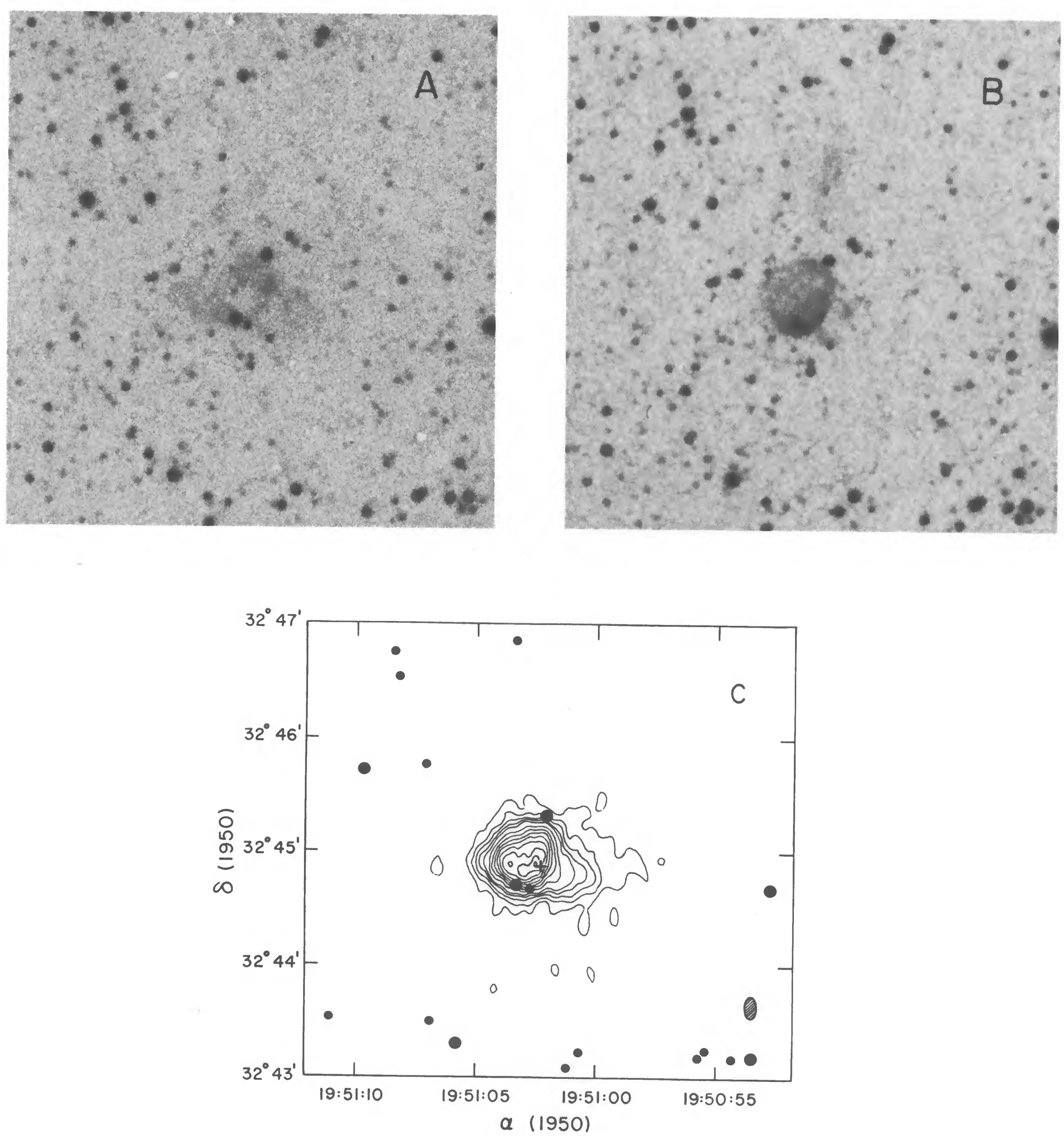

FIG. 2.—Comparison of the Hα + [N II], [O III], and 6 cm radio radiation from the core region of CTB 80. (*a*) Hα + [N II] image enlarged from Fig. 1. (*b*) [O III] image obtained with a Carnegie Image Tube on the no. 1–91 cm telescope at KPNO. The apparent emission ~1′ north of the core is residual phosphor glow from a focus star and is not real. (*c*) The 6 cm radio map of the core by Angerhofer *et al.* (1981). (Note: not all of the contours from the original map are shown.) The positions of several of the brighter stars visible on the photographs are indicated for reference, and the nominal position of the X-ray point source proposed by Becker, Helfand, and Szymkowiak (1982) is marked by a " + ."

TABLE 2

CTB 80 SPECTROPHOTOMETRIC OBSERVATIONS

UT Date	Telescope and Instrument	Filament Observed	Integration Time (s)	Slit Size (arc sec)	Resolution (Å)	Spectral Coverage (Å)
1980 Sep 6	KPNO 2.1 m; IIDS	SW	2000	6.1	18	3600—7000
1980 Sep 9	KPNO 2.1 m; IIDS	SW	2400	6.1	18	3600–7000
1980 Oct 15	McGraw-Hill 1.3 m; Reticon	SW	1800	4 × 40	5	5700–7400
1982 Sep 25	FLWO 1.5 m; Z-machine	NE	4200	3.1 × 12.6	8	4600–7000
1982 Sep 26	FLWO 1.5 m; Z-machine	NE	3600	3.1 × 12.6	8	4600–7000
1982 Sep 26	McGraw-Hill 1.3 m; Reticon	CORE	1800	3 × 20	10	3600–7000
1982 Sep 29	McGraw-Hill 1.3 m; Reticon	SSW	3000	5.6 × 40	12	4300–7000

instrumental response functions from separate standard stars agreed to within $\pm 25\%$ for each night, and we estimate that the absolute Hβ fluxes shown at the bottom of Table 3 are known to within a factor of 2. (Note that these are fluxes through slits of different sizes, as indicated in Table 1). Ratios between lines that are at least half the strength of Hα should be good to within 25% with considerably larger errors possible for the weaker lines. The Mount Hopkins spectra are somewhat less accurate due to flexure problems in this system. Comparison to other data obtained at Mount Hopkins indicates that the Hβ fluxes may have been underestimated relative to Hα in this data, simulating a higher reddening.

Observed and reddening corrected line intensities are presented in Table 3, on a scale where Hβ = 100. The spectra were corrected for reddening using the method described by Miller and Mathews (1972) and assuming an intrinsic ratio of Hα/Hβ = 3.0. This is consistent with the expectations of photoionization or shock heating (Brocklehurst 1971; Raymond 1979; Shull and McKee 1979) within the accuracy of the observations. The values of $E(B-V)$ so derived are listed at the bottom of Table 3 and range from 0.7 to 1.0 mag. The blue end of the spectrum at position SSW is very noisy, and no reddening estimate could be made. The value of $E(B-V) = 0.8$ for the core position is somewhat lower than the value of 1.0–1.4 estimated for this region by AWM (1980), although both values could be affected significantly by observational error in Hβ. The extinction of the NE filament appears to be slightly lower than that found for the core. Since the extinction may be patchy over the angular extent of the remnant, it is impossible to draw any firm conclusions about whether the NE filaments are associated with the rest of CTB 80 based on reddening.

III. DISCUSSION

a) The Distance to CTB 80

While the nonthermal radio emission from CTB 80 leaves little doubt that it is a SNR, the peculiarities of its radio structure and faintness of its optical filaments makes estimating the age and distance very difficult. AWM used a number of different methods to estimate a distance of 3 ± 1 kpc to CTB 80.

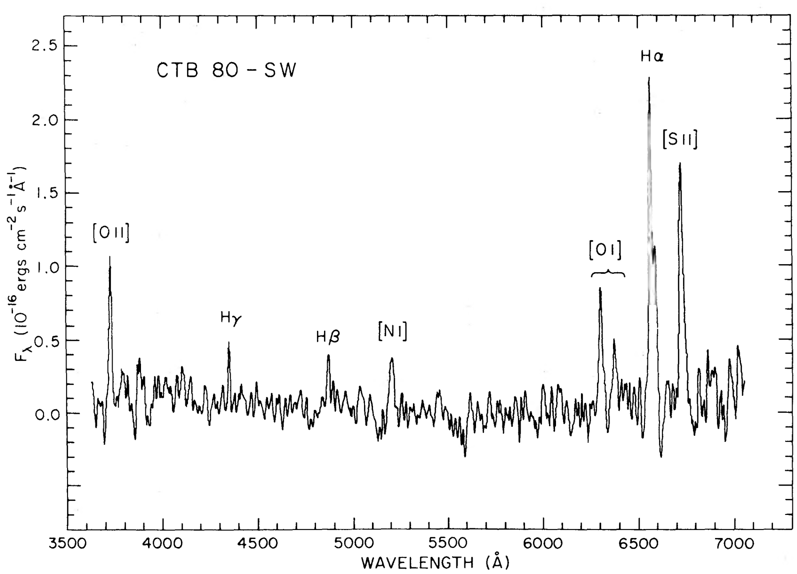

FIG. 3.—KPNO 2.1 m telescope spectrum of one of the outer filaments of CTB 80 (position SW), showing strong [O I] and [S II] emission characteristic of shock heated gas.

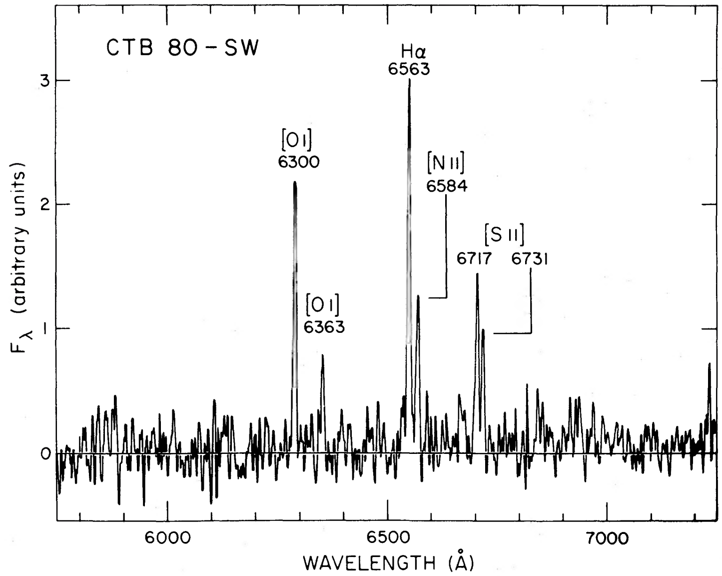

FIG. 4.—McGraw-Hill 1.3 m telescope red spectrum of position SW in CTB 80, showing [N II] resolved from Hα and separating [S II] λ6717 from λ6731. The filament observed was the same as in Fig. 3, but a larger slit was used (see text).

However, some of the methods used are unreliable, especially when applied to CTB 80. The peculiar outer structure of CTB 80 makes the definition of "diameter" ambiguous and the use of a standard Σ-*d* relation (cf. Clark and Caswell 1976) is questionable. Also, line ratio–diameter correlations for galactic SNRs (Daltabuit, D'Odorico, and Sabbadin 1977) have been shown to be due largely to abundance variations and selection effects (Fesen 1981; Binette *et al.* 1982). Of the remaining ways of estimating the distance, the optical reddening versus distance may be the most applicable to CTB 80. AWM used photometry of O and B stars in the vicinity of CTB 80 to establish the reddening as a function of distance out to about 3 kpc (see Fig. 9 of AWM). Their reddening estimates placed CTB 80 beyond 3 kpc, but probably not beyond 5 kpc. The somewhat lower reddening estimates of the present paper argue for a distance of about 2.5 kpc [assuming $\langle E(B-V)\rangle \approx 0.8$], with dispersion in the reddening versus distance curve and observational error causing an uncertainty of at least ±1.5 kpc.

Recent 21 cm radio measurements of the region surrounding CTB 80 have been obtained by E. Grayzeck and P. Angerhofer (1983, private communication) at Arecibo. Although analysis of these data is incomplete, a cloud which may be interacting with CTB 80 on the western side has tentatively been identified. Interpretation of the velocity of this cloud assuming a standard galactic rotation model would indicate a distance of

TABLE 3

OBSERVED, $F(\lambda)$, AND REDDENING CORRECTED, $I(\lambda)$, EMISSION-LINE INTENSITIES RELATIVE TO Hβ = 100

Line ID	λ	SW Low Disp.		SW High Disp.		SSW		NE		Core		90 km s⁻¹ Shock Model[a]
		$F(\lambda)$	$I(\lambda)$	$F(\lambda)$	$I(\lambda)$	$F(\lambda)$	$I(\lambda)$	$F(\lambda)$	$I(\lambda)$	$F(\lambda)$	$I(\lambda)$	
[O II]	3727	364	921	...	...	...	...	...	...	250:	530:	915
[Ne III]	3869	...	...	...	...	...	...	...	...	60:	115:	...
Hβ	4861	100	100	...	...	100:	...	100:	100:	100	100	100
[O III]	4959	...	...	...	...	...	...	...	...	155	145	50
[O III]	5007	<100	<94	...	...	142:	...	<40	<35	440	440	150
[N I]	5200	100:	77:	...	...	...	...	...	...	...	...	36
[O I]	6300	366	144	637	251	100:	...	149	76.9	108:	50:	33
[O I]	6364	148	58	228	89	...	...	54:	27:	...[a]	...[a]	11
[N II]	6548	144	50[c]	124	43	72[c]	...	75	35	135	57[c]	66
Hα	6565	865	300	865	300	267	...	630	300	709	300	321
[N II]	6584	433	150	367	127	217	...	239	112	641	266	197
[S II]	6717	939	303	416	134	131	...	369	165	437	172	146
[S II]	6731			330	106	96	...	197	88.3	337	133	120
$F(\text{H}\beta)$[d]		4.7 E-16		...		3.2 E-14		9.0 E-15		6.2 E-15		...
$E(B-V)$		1.0		(1.0)		...		0.7		0.8		...

NOTE.—: indicates large uncertainty in line flux.
[a] From Shull and McKee 1979.
[b] Line present, but too noisy to measure.
[c] [N II] 6548 blended with Hα; number assumes λ6584/λ6548 = 3.0.
[d] In ergs cm⁻² s⁻¹.

1.5–2.0 kpc, with a large uncertainty because of the nearness to the tangential point along the line of sight. This is at least qualitatively in agreement with a somewhat closer distance for CTB 80 than previously recognized. Below we will assume a distance of 2.5 kpc, and a parameter, $d \equiv$ (distance/2.5 kpc), will be included to allow scaling to other distances.

While CTB 80's outer radio structure is irregular, the three radio lobes extend approximately an equal angular distance ($\sim 35'$) to the east, north, and southwest of the central source. If we choose this as the "radius" of the outer structure, then it has a linear radius of $25d$ pc. The smaller inner core of emission would have a diameter of only $\sim 0.6d$ pc. The filaments to the northeast are about 50′ from the core, or a distance of $36d$ pc.

b) The Age of CTB 80

Strom, Angerhofer, and Velusamy (1980) have suggested that CTB 80 may be the result of the historical supernova of A.D. 1408 (see Clark and Stephenson 1977), but as pointed out by van den Bergh (1980), this would require expansion velocities of order $v_{ex} \sim c/3$ to account for the extent of the outer radio lobes. If the optical filaments to the northeast are really part of CTB 80, even higher velocities are required. While velocities of this magnitude have been inferred for the jets of SS 433 (Liebert *et al.* 1979; Margon, Grandi, and Downes 1980, and references therein), there is no evidence for jetlike structures or high-velocity material in the core of CTB 80, and the need for three jets (one for each of the main radio lobes) is particularly disturbing.

Another possibility is that only the core region is a result of the A.D. 1408 event. Assuming the distance and angular diameter mentioned earlier, this would require an average expansion velocity of $v_{ex} \approx 510d$ km s^{-1}. This is slower than the expansion velocities seen in other young SNRs such as Cas A or the Crab Nebula, and yet it is an order of magnitude larger than the actual expansion velocity measured for the core region of CTB 80 by AWM (i.e., $v_{ex} \lesssim 50$ km s^{-1}). It is unlikely that such a dramatic deceleration could have taken place since 1408, especially since the deceleration would have to take place very uniformly to maintain the apparent shell structure seen in the central region in [O III] and radio. The low densities and low velocity of the core make an association of the A.D. 1408 supernova with the core of CTB 80 improbable.

Becker, Helfand, and Szymkowiak (1982) discuss possible evolutionary trends in the X-ray luminosity and the ratio of X-ray to radio luminosities of a number of Crab-like SNRs including CTB 80. While there are theoretical reasons for believing that evolutionary effects may exist, the use of this theory to establish ages necessarily assumes that all Crab-like remnants follow a similar evolutionary track. For instance, based on this evolutionary picture, Becker, Helfand, and Szymkowiak (1982) argue against the association of the Crab-like remnant 3C 58 with the historical supernova of A.D. 1181 and instead suggest that it is considerably older than the Crab Nebula (SN 1054). However, recent optical spectra of 3C 58 by Fesen (1983) indicate expansion velocities of ~ 1000 km s^{-1}, much larger than previously seen; this makes the association of 3C 58 and SN 1181 much more likely. If two Crab-like remnants which are so similar in age can be so diverse in terms of their observed characteristics, one cannot apply this theory to determine accurate ages.

Nonetheless, the evolutionary picture might still apply in a broader sense to classify the remnants as "young" or "old." The ratio and X-ray data have now provided ample evidence for the inclusion of the central part of CTB 80 in the class of Crab-like remnants (see Becker, Helfand, and Szymkowiak 1982; Seward 1983). The ratio of the size of the outer radio structure to the inner X-ray core as well as the X-ray and radio luminosities for CTB 80 are all closer to those of Vela X than to the Crab Nebula or 3C 58. Vela X has an age estimate of roughly 12,000 years based on the spin-down rate of its pulsar (cf. Reichley, Downs, and Morris 1970). This age may only be approximate (for instance, see discussion by Stothers 1980), but it serves to establish Vela X as a relatively old Crab-like SNR. Based on the similarities discussed above, we suggest an age for CTB 80 of closer to 10^4 yr than 10^3 yr.

c) The Extended Structure of CTB 80

The extended Hα + [N II] emission seen in Figure 1*a* lies roughly in the direction of two of the three outer radio lobes. Figure 5 shows the 49 cm Westerbork map of CTB 80 by Angerhofer *et al.* (1981) along with a schematic representation of the extended optical filamentary structures. The brightest collection of filaments, including the SW position that we observed spectroscopically, can be seen $\sim 10'$ west of the core region and extending to the southwest. These filaments are roughly coincident with the northwest side of the southwest radio lobe but can be seen outside the lowest radio contour in places. Position SSW, which is barely visible on the POSS red print, is near the tip of the southwest radio lobe and is outside of the region shown in Figure 1*a*. Besides these filaments, some faint, diffuse emission is also present along most of the southwest radio lobe. Another area of diffuse emission is visible on the original plate, especially to the north and slightly west of the core (see Fig. 5); this may be correlated to a portion of the western edge of the northern radio lobe. However, no optical filaments have been detected in Hα + [N II] along the strong southern radio ridge that connects the eastern and southwestern radio plateau and lobes or in the radio lobe to the east of the core out to $\sim 15'$.

The strong [S II], [N II], and [O I] emission relative to Hα seen in the spectra of the outlying filaments of CTB 80 is similar to that seen in other SNRs. In conjunction with the nonthermal radio emission, this indicates that the filaments are probably shock heated. In Table 3, a 90 km s^{-1} shock wave model from Shull and McKee (1979) is shown for comparison to the reddening corrected line strengths. Except for the strengths of the neutral species, the model reproduces the observed relative line intensities quite well. The lack of agreement for the [O III] lines is not serious, as these lines are very sensitive to shock velocity around 90 km s^{-1} (cf. Shull and McKee's 80 km s^{-1} model, where I(O III) $= 0.07I(\mathrm{H}\beta)$, well below the upper limit for the well-observed SW position). However, the [O III] lines get strong and remain strong in the models with shock velocity greater than 90 km s^{-1}, and this may represent an upper limit to the shock velocity in the observed outer filaments.

Direct comparison of observations and shock models must not be overinterpreted, however. Recent observations in the Cygnus Loop by Fesen, Blair, and Kirshner (1982) have demonstrated that the spectra of individual filaments may represent some fraction of the cooling zone behind the shock, while tabulated line intensities for models represent the integrated line intensities throughout the entire recombination and cooling zone. Such an interpretation could account for the difference between the observed and predicted line intensities of [N I] and [O I].

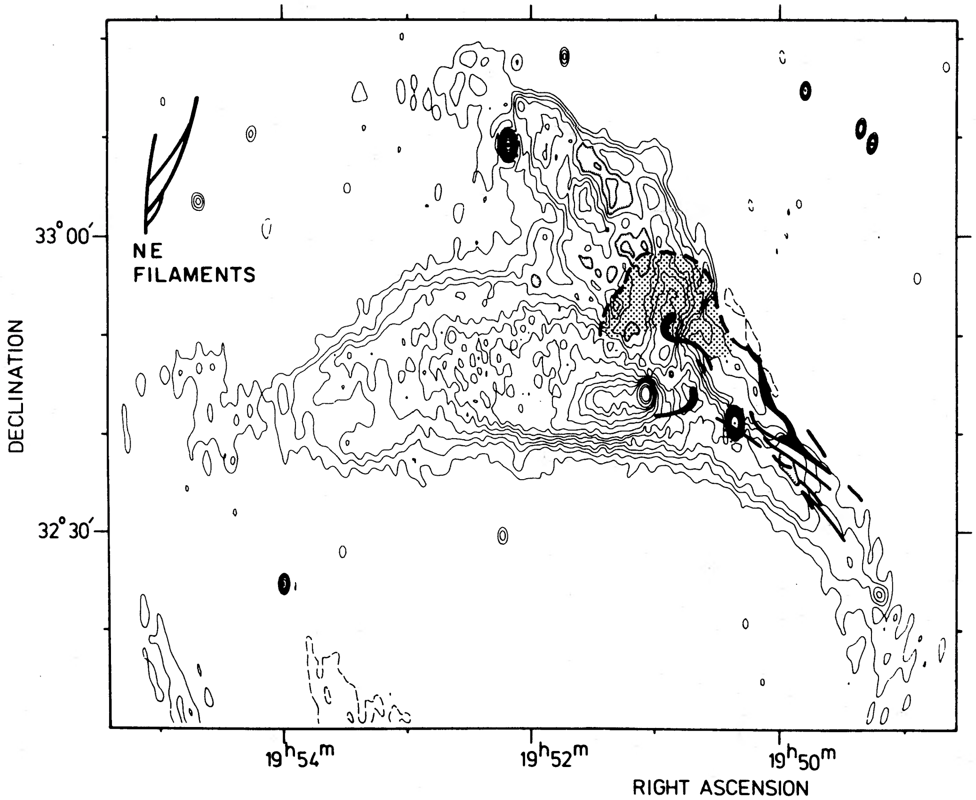

FIG. 5.—Westerbork 49 cm radio map of CTB 80 from Angerhofer *et al.* (1981) with the filaments visible on the Hα + [N II] photographs shown schematically for comparison. The dashed line and dotted region shows the extent of a region of patchy, diffuse emission that is visible on the original plate. The location of the northeast filaments are also shown.

The density-sensitive doublet of [S II] λλ6717, 6731 can be measured most accurately in the high dispersion spectrum of position SW (see Fig. 4). Using the recent cross sections of Pradhan (1978), *A*-values from Mendoza and Zeippen (1982), a five-level atom calculation, and assuming these lines are formed at about $T_e \approx 10^4$ K, we find $N_e \approx 200$ cm^{-3}. The observation at SSW is consistent with lower densities or even the low density limit ($N_e < 100$ cm^{-3}), although this observation is less accurate. These densities are typical of old, evolved SNRs such as the Cygnus Loop (Fesen, Blair, and Kirshner 1982) and IC 443 (Fesen and Kirshner 1980), but are much lower than the densities in young SNRs such as Cas A (Chevalier and Kirshner 1978) or the Crab Nebula (Fesen and Kirshner 1982).

The relationship of the northeastern filaments to CTB 80 is uncertain. The photograph of the northeast field (Fig. 1*b*) shows that these filaments are more diffuse than the filaments seen in the southwest, but some structure is present. The position of these filaments is schematically shown in Figure 5 relative to the 49 cm radio observations. If one ignores the "lobe" structure of the radio emission for the moment and simply extends a semicircular arc between the faintest radio contour in the east and north, one finds that these filaments are only slightly farther to the northeast. With the very irregular outer structure of CTB 80, it is not reasonable to exclude these filaments from CTB 80 based on positional evidence alone.

Unfortunately, the spectrum at position NE does not allow a convincing determination of whether the filaments are part of CTB 80. The spectrum is very similar to that seen at position SW, and the strong [S II] emission relative to Hα suggests that the filaments are shock heated, as was suspected by van den Bergh (1982). However, this conclusion is tempered by the fact that no nonthermal radio emission is seen and no [O III] temperature measurement is available for confirmation.

Although not obious on Figure 1*b*, visual inspection of this region on the POSS prints reveals that the NE filaments lie roughly along the border between a region of high (to the west) and low (to the east) obscuration. This could also be interpreted in two ways. The filaments could be part of CTB 80 extending out from behind a region of heavy obscuration into a relatively clear line of sight; this would account for the spectral similarities to other parts of CTB 80. Alternatively, the filaments could be caused by the interaction of an unrelated slow shock wave (perhaps from a very old, previously unidentified SNR) with a large interstellar cloud. This would explain the position of the filaments along the edge of a region of heavy obscuration. In any event, we cannot unequivocally state whether the NE filaments are related to CTB 80 or not.

d) The Central Region of CTB 80

Careful comparison of the [O III] and Hα + [N II] images of the core (see Fig. 2) reveals interesting differences. The [O III] image shows a well-defined shell of emission which is brightest along the southwestern rim. Two small knots of [O III] emission extend to the southwest from the shell. In contrast, the Hα + [N II] image shows a much more irregular ring that is brightest in the northwest and southeast. A ridge of Hα + [N II] emission which corresponds to the brightest part of the [O III] shell can be seen, but faint, diffuse Hα emission extends about 15″ farther to the east and southwest from the [O III] shell. Since a radial velocity study of this region in Hα, [N II], and [S II] by AWM provided evidence for a shell structure expanding at $\lesssim 50$ km s^{-1}, a similar study using [O III] might show this structure more clearly.

Our spectrum of the core encompassed most of the southwestern limb of this apparent [O III] shell and is not well suited to deriving the radial velocity of the [O III] gas (half-width at zero intensity for $\lambda 5007 \approx 400$ km s^{-1}, which was the instrumental resolution). However, since the extent of the [O III] emission is less than that of Hα + [N II], the [O III] shell is probably not expanding rapidly. We also note that the smooth morphology of the [O III] emission is much different than the "knotty" appearance of the fast-moving oxygen knots in young remnants such as N132D or 1E 0102−72 in the Large Magellanic Cloud (Lasker 1978; Tuohy and Dopita 1983).

The 6 cm Westerbork observations from Angerhofer *et al.* (1981) are also shown in Figure 2*c*. The [O III] shell corresponds quite well with the steep gradient seen in the radio data, although the radio indicates a filled-center distribution, and not a shell. The radio distribution is not entirely symmetric with respect to the center: two peaks in the radio are indicated, with the brighter peak being on the western side of the central core.

A faint stellar object can be seen near the center of the [O III] shell in Figure 2*b*, but a spectrum of this object (H. Ford and G. Jacoby, 1982, private communication) indicates that it is a late-type star. While no radio point source has been detected in the core of CTB 80, an X-ray point source which contributes 25%–30% of the total X-ray flux has been inferred by Becker, Helfand, and Szymkowiak (1982) from *Einstein* HRI data. The position of maximum X-ray brightness given by Becker, Helfand, and Szymkowiak (1982) (position quoted to $\pm 3''$) is shown in Figure 2. There is no apparent optical source at this location to the limit of the POSS, although this position is very close to the brightest emission peak in the radio data.

AWM obtained spectra of two knots in the core and found substantial variations in some relative line intensities. The slit position for our spectrum, chosen from the [O III] photograph, included part of their "knot 1" and extended to the southwest along the brightest [O III] region. The reddening as indicated by our spectrum is considerably lower than found by AWM. Since Hβ is weak in all of these spectra, this difference is largely attributable to observational error in the Hβ line. A $\pm 30\%$ change in the strength of Hβ would cause a change in $E(B-V)$ of (+0.34, −0.24) mag. The ratio of the [S II] lines indicates a density of $N_e \approx 100$ cm^{-3}, which is somewhat lower than the value found by AWM for knot 1 (even after differences in atomic parameters are taken into account). This could be due to the different slit sizes used as well as observational error.

The presence of strong [S II] emission in the core of CTB 80 prompted AWM to conclude that the core emission was the result of shock heating. However, this conclusion is difficult to reconcile with other observed parameters. The presence of strong [O III] emission seems to require shock velocities greater than 90 km s^{-1}, while the velocity data in the core indicate much lower velocities. It is not clear how such a fast shock could be present in this central region if the slower shocks indicated for the remainder of the remnant have expanded to much larger distances.

The similarities of the X-ray and radio properties of the core to the Crab Nebula suggests another possibility: perhaps the core filaments in CTB 80 are *photoionized*. Because the [O III] temperatures in the Crab Nebula's filaments are lower than normally seen in shock-heated gas (~15,000 K; see Fesen and Kirshner 1982), the filaments in the Crab are believed to be photoionized by the so-called amorphous region (which in turn is powered by energy from the Crab pulsar). Spectra of filaments in the Crab Nebula (Miller 1978; Davidson 1978, 1979; Fesen and Kirshner 1982) show a wide variety of relative line intensities but are not too unlike the CTB 80 core spectra, including strong [S II] relative to Hα. The largest discrepancy in the strong lines [$> I(\mathrm{H}\beta)$] is the strength of [O III] λλ4959, 5007, which are generally much weaker in the core of CTB 80 than in the Crab. Photoionization models of the Crab Nebula by Henry and MacAlpine (1982) show that decreasing the input ionizing flux can dramatically lower the strength of the [O III] lines. If the core of CTB 80 is an old Crab Nebula, its smaller size and weaker [O III] may be the result of a weaker ionizing flux.

This does not mean that the optical emission in the Crab Nebula and CTB 80's core are directly analogous. The Crab filaments are rapidly expanding and show signs of chemical enrichment; they are ejecta from the exploded star. If CTB 80's core really represents an old Crab Nebula, this rapidly moving ejecta would have expanded out to much larger distances. The spectra and morphology of the core region of CTB 80 suggest that the optical emission comes from interstellar (or circumstellar) gas that has been swept into a shell-like structure, perhaps by a wind from the central source, or by low frequency electromagnetic waves as described by Gunn and Ostriker (1971).

No amorphous region is optically observed in CTB 80 (which is probably not surprising since one is not seen in Vela X and Vela X is both closer and less reddened than CTB 80) and the characteristics of the point source (presumably an old pulsar) are very poorly known. We can perform a crude calculation, however, to estimate whether ionization by nonthermal electrons can account for the observed optical luminosity of the core.

From the slit size, area of the optical core on the sky and surface brightness considerations, we estimate that ~5% of the core's Hα emission entered the slit. Correcting the observed Hα for reddening (assuming $E(B-V) = 0.8$) we find the total core luminosity in Hα to be

$$L(\mathrm{H}\alpha) \approx 4.2 \times 10^{33} d^2 \text{ ergs s}^{-1} , \quad (1)$$

which requires $1.4 \times 10^{45} d^2$ recombinations s^{-1}. [Note: from eq. (1) and Table 3, the total optical luminosity of the core is roughly $L_{\mathrm{op}} \approx 8L(\mathrm{H}\alpha) = 3.4 \times 10^{34}$ ergs s^{-1}.] As a consistency check, we can compare this to what would be expected theoretically, viz.,

$$L_{\mathrm{th}}(\mathrm{H}\alpha) = Vfh\nu_{\mathrm{H}\alpha} N_e N_p \alpha_{\mathrm{H}\alpha}{}^{\mathrm{eff}} , \quad (2)$$

where $N_e = N_p \approx 100$ cm^{-3}, $\alpha_{\mathrm{H}\alpha}{}^{\mathrm{eff}}$ is the effective recombination rate coefficient for Hα (taken from MacAlpine 1971), V is the volume of the core in cm^{-3}, and f is the Hα-emitting fraction of this volume. Assuming a radius of 0.3d pc for the core, we find

$$L_{\mathrm{th}}(\mathrm{H}\alpha) = 1.0 \times 10^{34} f d^3 \text{ ergs s}^{-1} . \quad (3)$$

Comparing equation (3) to equation (1), we can estimate $f \approx 0.42 d^{-1}$; that is, the emitting fraction is somewhat less than half of the volume of the core, which is consistent with its patchy, shell-like appearance.

In passing, we note that the mass of the core can be estimated using the formula

$$M = m_H N_e V f g \,, \tag{4}$$

where m_H is the mass of a hydrogen atom. Using numbers from above, $M \approx 0.1 d^2 M_\odot$, which is considerably less than similar estimates for the Crab Nebula (cf. Kirshner 1974).

The radio properties of the core can be used to estimate the ionization due to nonthermal electrons. Angerhofer *et al.* (1981; see their Table 4) use their radio observations with equipartition arguments to calculate a minimum total energy for the core of $E_{tot} = 1.7 \times 10^{45} d^{17/7}$ ergs, assuming a radio spectrum from 10 MHz to 10 GHz. One-half of this energy would be in nonthermal electrons, and these electrons would have energies in the range $\sim$100 MeV to $\sim$3.4 GeV (assuming the frequency range from above). Ionization cross sections for electrons of these energies can be obtained by using an exponential extrapolation from the low-energy experimental values of Kieffer (1969), with the result that electrons at the low-energy end of the distribution have cross sections 250 times those at the high-energy end. As a first-order approximation, we will assume all of the electrons to be $\sim$100 MeV, which should overestimate the ionization rate.

The ionization rate due to nonthermal electrons can now be estimated using the formula,

$$C_i(E) = \tfrac{1}{2}\sigma(E) c N_H \, d^{16/7} \text{ s}^{-1} \,, \tag{5}$$

where E is the energy per electron, $\sigma(E)$ is the ionization cross section for the electrons, c is the speed of light, and N_H is the neutral hydrogen density in cm^{-3}. For $E = 100$ MeV, $\sigma = 1.1 \times 10^{-21}$ cm^2, we have

$$C_i(100 \text{ MeV}) = 1.6 \times 10^{38} N_H \, d^{16/7} \text{ ionizations s}^{-1} \,. \tag{6}$$

Hence, even if hydrogen is mostly neutral (i.e., $N_H = 100$ cm^{-3}), the ionization rate due to nonthermal electrons is too low by almost a factor of 10^5 to account for the optical core emission.

Another possible source of ionization could be the ultraviolet and X-ray emission from the core. The X-ray luminosity can be estimated if the count rate, spectrum, and neutral hydrogen column density, n_H, are known. Using the relation of color excess to n_H (cf. Gorenstein 1975; Ryter, Cesarsky, and Audouze 1975), $E(B-V) = 0.8$ implies $n_H \approx 5.7 \times 10^{21}$ cm^{-2}. Assuming a Crab-like X-ray spectrum (Dolan *et al.* 1977), and an HRI count rate of 0.009 counts s^{-1} (Becker, Helfand, and Szymkowiak 1982) then yields

$$L_x(0.1\text{–}4 \text{ keV}) \approx 5.1 \times 10^{33} d^2 \text{ ergs s}^{-1} \,. \tag{7}$$

This is comparable to the Hα luminosity from equation (1). We note that the HRI detector is not very sensitive to extended, diffuse emission. A preliminary analysis of an unpublished IPC image of CTB 80 (Seward 1983) yielded an estimate of $L_x \approx 8 \times 10^{33}$ ergs s^{-1}, for the core region, assuming a Crab-like spectrum and extinction. Since the Crab Nebula is less reddened than CTB 80 [$E(B-V) = 0.5$ for the Crab; Wu 1981], the X-ray luminosity of CTB 80's core may be larger than 10^{34} ergs s^{-1}. The *Einstein* X-ray data for CTB 80 are being reprocessed (F. D. Seward and Z-R. Wang 1983, private communication) and should allow this number to be refined.

This only represents the fraction of the X-ray luminosity that escapes; we have no information as to how much of the X-ray emission gets absorbed in the core. However, because of the ν^{-3} dependence in the photoionization cross section for hydrogen, it is doubtful that the shell could provide significant optical depth in the *Einstein* bandpass, even if $N_H = 100$ cm^{-3}. Hence, direct absorption of X-rays is probably not an efficient ionization mechanism.

Unfortunately, no direct information is available on the spectral distribution of the X-ray emission from CTB 80's core. A power-law distribution is indicated for other Crab-like remnants (Becker, Helfand, and Szymkowiak 1982, 1983; Kirshner 1974). If this is also the case for the core of CTB 80, its large X-ray luminosity would imply significant ultraviolet emission (although the amount would depend on the exact shape of the power law). At ultraviolet wavelengths, the photoionization cross section for hydrogen increases. In particular, near the Lyman limit we have $a_0 \approx 6 \times 10^{-18}$ cm^{-2}. To provide an optical depth of $\tau \approx 1$, we need to have

$$N_H \, dl \approx \frac{1}{a_0} = 1.7 \times 10^{17} \text{ cm}^{-2} \tag{8}$$

(cf. Osterbrock 1974). Hence, with $dl \approx 0.3d$ pc $= 9.2 \times 10^{17} d$ cm, neutral hydrogen densities greater than $\sim$0.2 cm^{-3} would provide significant optical depth near the Lyman edge. More detailed information on the X-ray and ultraviolet spectrum and N_H will be necessary to investigate this possibility more quantitatively. However, if the core of CTB 80 is photoionized, the ultraviolet continuum would appear to provide the most plausible energy source.

IV. CLOSING REMARKS

The "photoionized" picture for the core of CTB 80 potentially causes fewer problems than the "shock-heated" picture, although additional work is needed for verification. An [O III] temperature measurement for the core would be very important, although the combination of faint filaments and moderate reddening will make this observation difficult. Further information on the suspected point source in the core, including a radio or optical identification, would also be crucial to the further understanding of this object. The reprocessed X-ray data should allow the photoionized picture to be tested.

Besides determining whether the core of CTB 80 is photoionized, many other problems remain. The northeastern filaments remain enigmatic and the radio detection of these filaments would help clarify their relationship to CTB 80. The cause of the three-lobed outer radio structure is not understood, although presumably it is due to an inhomogeneous surrounding medium. Further radio studies of the region and radial velocity studies of both the core and outer filaments would aid in understanding the strange morphology of this interesting remnant.

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