THE ASTROPHYSICAL JOURNAL, 247:148–151, 1981 July 1

THE OPTICAL EMISSION FROM THE SUPERNOVA REMNANT CTA 1

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Received 1980 December 8; accepted 1981 January 6

ABSTRACT

Interference filter photographs have been obtained of faint filaments of the supernova remnant CTA 1 which reveal this remnant's overall optical structure. The remnant's nebulosity shows very strong [O III] emission and has a generally diffuse appearance. Although the radio contours at 2695 MHz coincide with many of the features of the optical nebulosity, in the northeast the optical emission extends considerably beyond the radio emission. A spectrum of one position in the nebula shows strong [S II] $\lambda\lambda$6717, 6731 lines relative to Hα, which is consistent with the optical emission from a supernova remnant.

Subject headings: nebulae: individual – nebulae: supernova remnants — radio sources: general

I. INTRODUCTION

The extended galactic radio source CTA 1 ($l = 119\overset{\circ}{.}5$, $b = +10\overset{\circ}{.}2$) was first detected by Harris and Roberts (1960). Because four faint wisps of optical emission visible on the red print of the Palomar Observatory Sky Survey (POSS) agreed well with the position of the shell of radio emission (see Harris 1962), Harris and Roberts suggested that this radio source was a possible supernova remnant (SNR). Caswell (1967), who surveyed the object at 81.5 and 178 MHz, used Harris and Roberts's 960 MHz observation together with a 408 MHz measurement by Westerhout (reported by Harris 1962) to calculate a spectral index ($S \propto \nu^{-\alpha}$) for CTA 1 of $\alpha = +0.2 \pm 0.2$. Sieber, Haslam, and Salter (1979), combining their 2695 MHz observations with these results, obtained a revised spectral index of $\alpha = +0.30 \pm 0.05$. On the basis of radio morphology, spectrum, and polarization, Sieber *et al.* confirmed that CTA 1 is a supernova remnant.

The distance to CTA 1 is not well determined. Recent distance estimates using the Σ-D relationship have ranged from 1.0 to 2.0 kpc (Clark and Caswell 1976; Milne 1979; Caswell and Lerche 1979; Sieber, Haslam, and Salter 1979). With an angular size of about 107′, the SNR has a radio diameter of 47 (d/1.5 kpc) pc, where d is the remnant's distance in kpc.

The optical emission associated with CTA 1 is extremely faint. Van den Bergh, Marscher, and Terzian (1973), using deep-red Schmidt plates ($\lambda\lambda$6400–6700), confirmed the presence of exceedingly faint, structureless nebulosity near the positions of the strongest radio emission. However, the optical emission was too faint to be reproduced in their optical atlas of galactic supernova remnants. While the nebulosity *is* visible on the POSS, it is so faint that it can easily be missed (see Caswell 1967).

In this paper, we present an [O III] interference filter photograph of CTA 1, which shows for the first time the remnant's overall optical structure. We also present a spectrum taken at one position in the remnant's nebulosity.

II. OBSERVATIONS

In connection with an emission-line survey of the Milky Way (Parker, Gull, and Kirshner 1979), a special effort was made to photograph the known SNRs. Narrow passband interference filters were used to isolate the line emissions of [O III] (5010 Å, $\Delta\lambda = 28$ Å), Hα + [N II] (6570 Å, $\Delta\lambda = 75$ Å), [S II] (6736 Å, $\Delta\lambda = 50$ Å), and Hβ (4864 Å, $\Delta\lambda = 28$ Å). The photographs were made with these 127 mm clear aperture interference filters mounted in front of a 300 mm focal length f/2.8 Nikkor lens which formed an image on the cathode of a magnetically focused two-stage RCA image intensifier. The output of the image tube was lens-coupled to baked IIIa-J plates. The field covered is $7\overset{\circ}{.}1$ in diameter with 30″–40″ angular resolution. We photographed CTA 1 twice with each filter. Although the remnant is visible in Hα + [N II] and [S II], the images are too faint for reproduction and only an [O III] photograph is shown in Figure 1 (Plate 4).

We have obtained a spectrum at one location in the southern part of the remnant. The data were obtained on 1980 January 17 and 21 and on 1980 August 8 and 9 with an intensified Reticon spectrometer attached to the 1.3 m telescope at McGraw-Hill Observatory. The scans

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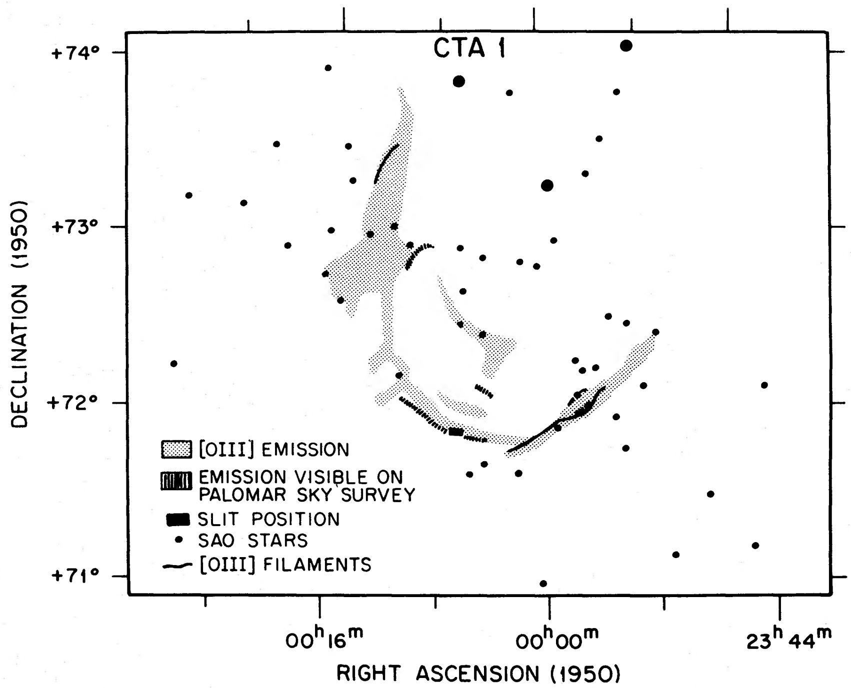

FIG. 2.—Sketch of CTA 1's optical nebulosity showing the position of the remnant's [O III] emission as well as the faint emission visible on the Palomar Sky Survey. The small rectangle indicates the position of the 4″ × 40″ slit but is not drawn to scale.

covered the spectral range of 3700–7400 Å with a resolution of about 12 Å. The position of the 4″ × 40″ slit is indicated in Figure 2 which also shows a sketch of the remnant's optical emission. The slit position corresponds to one of the patches of nebulosity visible on the POSS and on a deep-red Schmidt plate kindly lent to us by S. van den Bergh.

Total integration time on the subject was 12,600 seconds, with half as much time spent for sky measurement. Scans were corrected for atmospheric extinction using mean Kitt Peak values, the sky spectra subtracted, and the data placed on a linear wavelength scale. Flux calibrations were obtained through observations of white dwarfs whose absolute fluxes for given wavelength intervals are known (Oke 1974).

The combination of the extreme faintness of the optical emission, shorter sky integrations than for the object, and the necessity of moving off the object about 30′ south for sky measurement resulted in both poor statistics and imperfect sky subtraction. The combined reduced data for the four nights are shown in Figure 3, with the measured line fluxes relative to Hα listed in Table 1. The accuracy of the relative line strengths is estimated to be ± 30%, with the line strengths of the [O II] lines at λ3727 and λ7325 even more uncertain. Our estimated error for

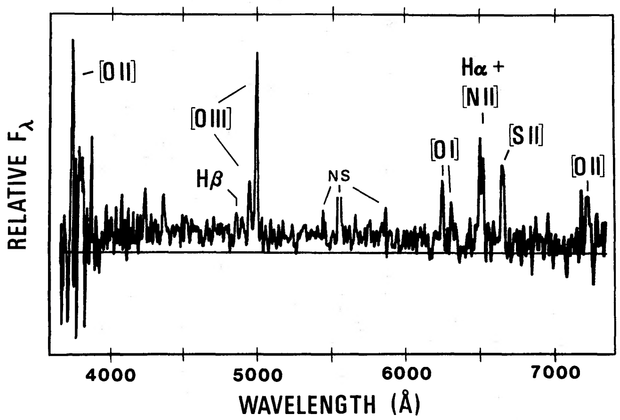

FIG. 3.—Spectrum of CTA 1. Relative flux per unit wavelength is plotted vs. observed wavelength. Imperfect sky subtraction resulted in the presence of several night-sky emission features. The intensity of the λ5577 night-sky emission has been artificially truncated; the [O I] λλ6300, 6364 intensity is mostly night-sky contamination.

TABLE 1

RELATIVE LINE INTENSITIES
$F(H\alpha) = 100$

λ(Å)	ID	$F(\lambda)$
3727	[O II]	(184)
4861	Hβ	(22)
4959	[O III]	58
5007	[O III]	192
6300	[O I]	<65
6563	Hα	100
6583	[N II]	86
6717	[S II]	76
6731	[S II]	60
7325	[O II]	(60)
$F(H\alpha)$[a]	...	1.6×10^{-14}

[a] ergs cm^{-2} s^{-1}.

the Hα flux is $\pm 50\%$. Only an upper limit is possible for the nebula's [O I] λ6300 intensity due to contamination by night-sky emission.

III. DISCUSSION

The optical nebulosity attributed to the remnant CTA 1 is seen best in the [O III] photograph (see Fig. 1). The emission appears asymmetrically distributed in almost a semicircular shape and covers an area of about $2.^\circ5 \times 2.^\circ0$. While this faint nebulosity is generally diffuse in appearance, there are some thin filaments visible in the northeast, south, and southwestern regions. The remnant's Hα + [N II] emission agrees in general with the distribution of the [O III] line emission, but is fainter. However, the brightest regions in our [O III] imagery do not always coincide with the brightest Hα + [N II] areas. For example, there appears to be no Hα + [N II] counterpart for the bright southwestern [O III] filament. The faint patches of nebulosity visible on the POSS are generally those regions which are brightest in our Hα + [N II] photographs. CTA 1's great visibility in [O III] relative to the other emission lines is similar to the SNRs G65.3+5.7 (Gull, Kirshner, and Parker 1977) and G126.2+1.6 (Blair *et al.* 1980) which were identified by the same technique. However, CTA 1's emission is not as filamentary as in these other remnants.

We have compared CTA 1's [O III] distribution with the high-resolution 2695 MHz contour map obtained by Sieber *et al.* In general, the ridges of the radio shell coincide with many [O III] features. In particular, the southwestern radio ridge coincides well with a bright, long (~45′) [O III] filament. There is also fair agreement between the radio emission detected near the center of the remnant and patches of faint [O III] emission. Little or no [O III] emission is visible in the area to the northwest of the remnant's center where the radio emission is weakest. The nebulosity visible on the POSS red print also corresponds very well to the brightest radio regions of CTA 1 observed at 2695 MHz.

However, in the northeast the optical emission extends much farther out from the center of the remnant than the 2695 MHz radio emission. While Caswell (1967) did not detect radio emission in this region at 81.5 MHz, Harris and Roberts's 960 MHz observations (see Harris 1962) show an extension of the radio contours in just about the right area (00^h10^m, $+73.^\circ5$). Despite this confusion at lower frequencies, some radio emission is likely in view of the widespread optical emission. A comparison of Sieber *et al.*'s observations with those of Caswell suggest that the lower frequency radio emission tends to extend to greater radial distances. Sieber *et al.* have suggested that this could be due to a steepening in the spectral index of the radio emission with increasing radial distance. Spectral changes have been seen in other SNRs such as IC 443 (Hill 1972), G65.3+5.7 (Reich, Berkhuijsen, and Sofue 1979) and G326.3−1.8 (Clark, Green, and Caswell 1975). The presence of similar spectral changes in CTA 1 could explain the reported differences in this remnant's radio emission.

The spectroscopic data listed in Table 1, although of low quality, suggest that the nebulosity belongs to a supernova remnant as judged by the relative strength of the [S II] λλ6717, 6731 emission compared to Hα. For the position we observed, the ratio of Hα/[S II] is close to 0.75, which is much smaller than seen in H II regions, and satisfies the usual criterion for identifying SNRs (i.e., Hα/[S II] $\lesssim 2.5$; see D'Odorico 1978). Because our slit position was selected from a red plate, not an [O III] plate, we observed a region where the [O III] emission was only of moderate strength compared to Hα + [N II]. Our observed ratio for [O III]/Hβ of more than 10 can be taken as an indication that larger values are present in some regions of the nebula. The electron density for CTA 1 cannot be accurately estimated from the observed ratio of the density sensitive [S II] λλ6717, 6731 lines because of poor photon statistics; however, the data suggest values smaller than 1000 $\mathrm{cm^{-3}}$. Although we may have marginally detected Hβ, we cannot give a meaningful estimate of the reddening to CTA 1 due to the large uncertainty in the Hβ intensity. However, if CTA 1 is at a distance of 1–2 kpc, the amount of extinction should be fairly large, with an $E(B-V)$ near 0.5 mag (FitzGerald 1968; Lucke 1978).

It is interesting to note that shock models produce strong [O III] emission only for shock velocities of 60 km $\mathrm{s^{-1}}$ or more (Raymond 1979; Shull and McKee 1979). If the pressure in the shocked filaments is indicative of the pressure throughout the remnant, we can use the Sedov solution (McKee and Cowie 1975) in a form that relates the distance to the observed properties of the remnant, viz.,

$$D = (E/n)^{1/3} V^{-2/3} \theta^{-1} \text{ kpc} ,$$

where E is the initial energy in units of 10^{50} ergs, n is the ambient density in particles per $\mathrm{cm^3}$, V is the velocity in 100 km $\mathrm{s^{-1}}$ units, and θ is the angular size in degrees. Using the velocity estimated from the [O III] emission, we infer $D > 790$ pc for $E/n = 10^{50}$ ergs $\mathrm{cm^3}$ and $D > 1.7$ kpc for $E/n = 10^{51}$ ergs $\mathrm{cm^3}$, which covers the usual range of supernova energies (Blair, Kirshner, and Chevalier 1981). This is reasonably consistent with the distances derived from radio surface brightness discussed in § I. For $D = 1.5$ kpc, $E/n = 6.8 \times 10^{50}$ ergs $\mathrm{cm^3}$, which is the same energy as derived for the Cygnus Loop by similar methods (Blair *et al.* 1980).

IV. CONCLUSION

Interference filter photographs of the supernova remnant CTA 1 show considerable optical nebulosity which has strong [O III] emission relative to that of Hα + [N II] and is generally diffuse. While much of the optical emission coincides with the radio emission observed by Sieber *et al.* at 2695 MHz, there is a significant optical extension away from remnant center to the northeast. A spectrum in the southern portion of the nebula indicates relatively large [O III]/Hβ and [S II]/Hα ratios.

Strong [O III] emission in CTA 1 as well as in G65.3+5.7 and G126.2+1.6 is significant. It suggests the possibility that other faint SNRs having large [O III]/Hβ ratios might have been overlooked in optical surveys using the strength of [S II] relative to Hα where both of these lines are weak. The survey technique of Parker, Gull, and Kirshner (1979) is particularly useful for finding these SNRs since it is much more sensitive than the POSS blue plate at λ5007.

The emission mechanism for this very strong [O III] emission relative to Hβ is uncertain. In shock wave models, the [O III]/Hβ ratio is always smaller than 9. In this remnant, we have observed [O III]/Hβ $\gtrsim 10$ in a region where [O III]/Hβ is not expected to be especially large. One suggested way to produce strong [O III] emission is by departure from a steady flow (Raymond *et al.* 1980). This hypothesis may be adequate for the localized regions of strong [O III] emission observed in the Cygnus Loop and IC 443 (Fesen and Kirshner 1980; Fesen, Blair, and Kirshner 1981), but it is not clear that it can account for the widespread strong [O III] emission seen throughout CTA 1 and also observed in G65.3 + 5.7 and G126.2 + 1.6.

Although CTA 1 is a very faint optical SNR, further work on this and similar SNRs would be useful. Higher resolution mapping at low and intermediate radio frequencies could investigate the presence of radio emission in all the optically visible regions. Also, it may be possible to estimate the shock velocity responsible for the optical emission by studying the radial velocities and line widths in the faint gas near the remnant's center. Finally, electron temperature estimates could be obtained for at least some of the brighter [O III] regions. It would be instructive to compare the electron temperature, density, and shock velocity of CTA 1's strong [O III] filaments to those found in other SNRs.

We would like to thank Dr. Sidney van den Bergh for loaning us his Schmidt plate of CTA 1. Research on supernovae at the University of Michigan is supported in part by NSF grant AST 77-17600. R. P. K. gratefully acknowledges the support of the Alfred P. Sloan Foundation.

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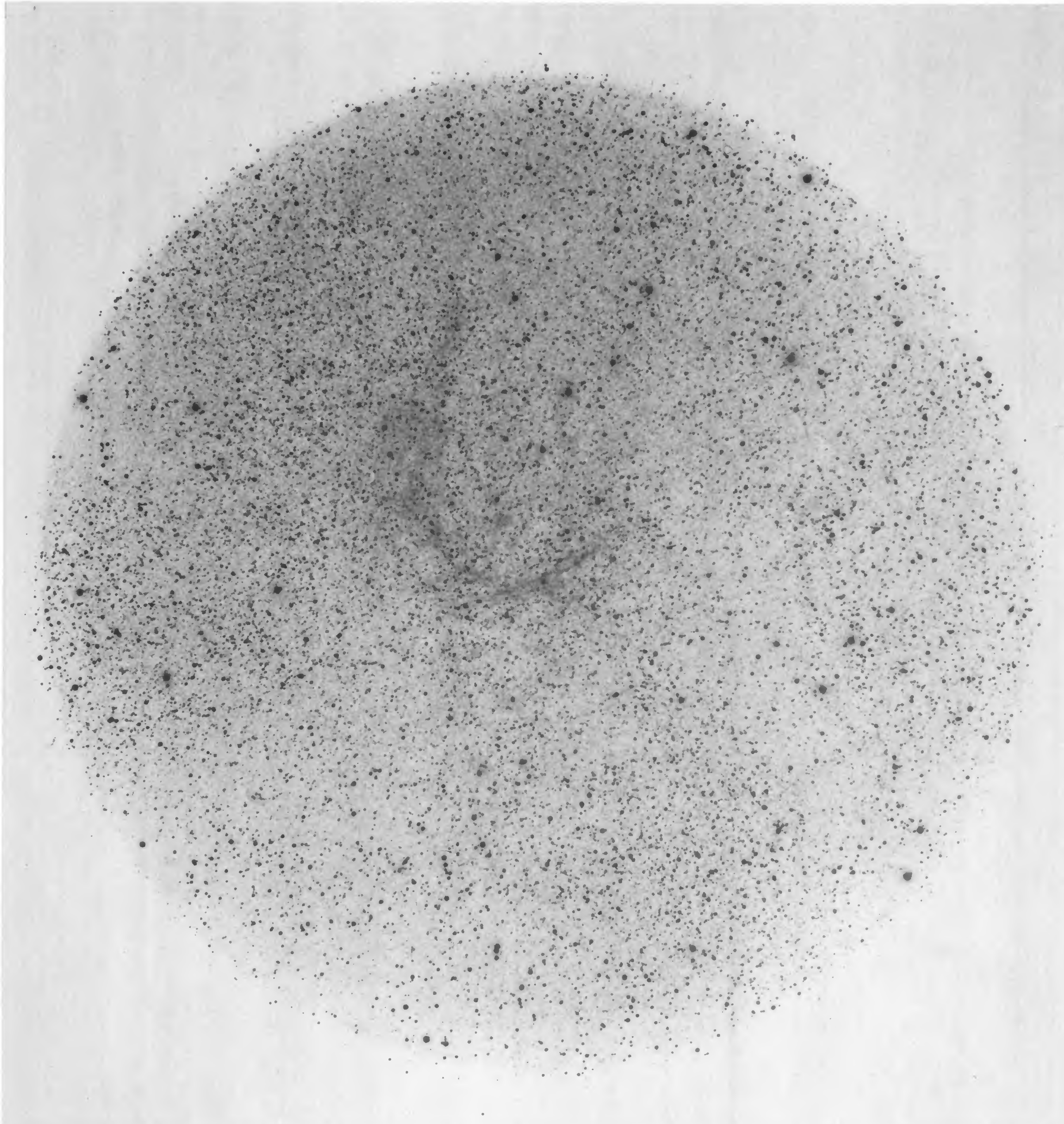

FIG. 1.—An [O III] interference filter photograph of the galactic supernova remnant CTA 1. North is at top, east to the left.

FESEN *et al.* (*see* page 148)