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SPECTROPHOTOMETRY OF W50: THE SUPERNOVA REMNANT AROUND SS 433

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ABSTRACT

We have obtained spectra of two regions of nebulosity associated with the radio supernova remnant W50 that surrounds SS 433. In general, the interpretation of the spectra supports the idea that the nebulosity is associated with the supernova remnant and is consistent with the association of W50 with SS 433. If the remnant is at a distance of 3.5 kpc, we find that the observed pressure in the optical filaments constrains the internal energy in the supernova remnant to $E \lesssim 8 \times 10^{50}$ ergs. We find that the optical filaments themselves are unlikely to be directly excited by the beams ejected by SS 433. The spectra of W50 show unusually strong lines of [N II], similar to those observed in Puppis A.

Subject headings: nebulae: supernova remnants — spectrophotometry

I. INTRODUCTION

The supernova remnant W50 was one of the objects on the list of Ryle *et al.* (1978), which associated SNRs with unusual compact radio sources. In this case, the associated object was found to be the unusual object SS 433 (Clark and Murdin 1978; Margon *et al.* 1979) which is a plausible candidate for the stellar remnant of the star that exploded to create the SNR. The excellent high-resolution radio map by Geldzahler, Pauls, and Salter (1980) shows that W50 forms a complete shell of emission centered on SS 433 with diameter 1°. Two semicircular "ears" to the east and west are an unusual feature of the radio morphology which has been linked by Begelman *et al.* (1980) to nonrelativistic beams ejected from SS 433.

Optical emission coincident with W50 has been detected by Zealey, Dopita, and Malin (1979) and by van den Bergh (1980). Some spectroscopic results have been reported briefly by Zealy, Dopita, and Malin (1979) and in more detail by Murdin and Clark (1980) and by Shuder, Hatfield, and Cohen (1980). In this *Letter* we present further data of good quality which are used to derive some interesting physical properties of W50 and to circumscribe the nature of the interaction of SS 433 with the surrounding interstellar gas.

II. OBSERVATIONS

As detailed in Table 1, we have used the Image Dissector Scanner at the KPNO 2.1 m telescope to obtain spectra of two regions in W50. The brighter region, which we call "W50 East," is visible on the Palomar Sky Survey as a faint arc of nebulosity, while the other region, "W50 West," is visible in the plate of van den Bergh (1980). Each of these locations is near an "ear" of the radio map.

Our data were obtained under photometric conditions with simultaneous sky and object measurements through a pair of 6″.1 diameter apertures separated by 99″.4. The data were reduced to fluxes through the observations of several standard stars and the assumption of a mean extinction table, using the KPNO reduction routines. The results are displayed in Figure 1 and tabulated in Table 2. Within each spectrum, the line strengths have probably been measured to 20%. For W50 East, the blue and red measurements were not made simultaneously, so that comparison of the data hinges on the absolute calibration for the spectra. This undoubtedly introduces errors somewhat larger than the uncertainty due to photon statistics alone.

We note that the ratio of Hα/Hβ is roughly 8, rather than 3, as observed in unreddened supernova remnants or pure recombination calculations. This reddening implies at least 2.7 mag of absorption in the visible. This result is consistent with the result found by Murdin and Clark (1980) who did not detect Hβ and inferred $A_v \approx 3.5$. As noted by Murdin and Clark, this absorption is large, but not as large as the $A_v \approx 7$ inferred for SS 433 from the strength of interstellar absorption. Inspection of the plate published by van den Bergh (1980) shows that the center of W50 is obscured by a very opaque region, while the optical emission is observed only in less thoroughly blocked zones. In a general way, the observed reddening values do not exclude the possibility that W50 and SS 433 are linked.

For convenience, we have also adopted $A_v = 2.7$ for W50 West, even though we did not measure Hβ there.

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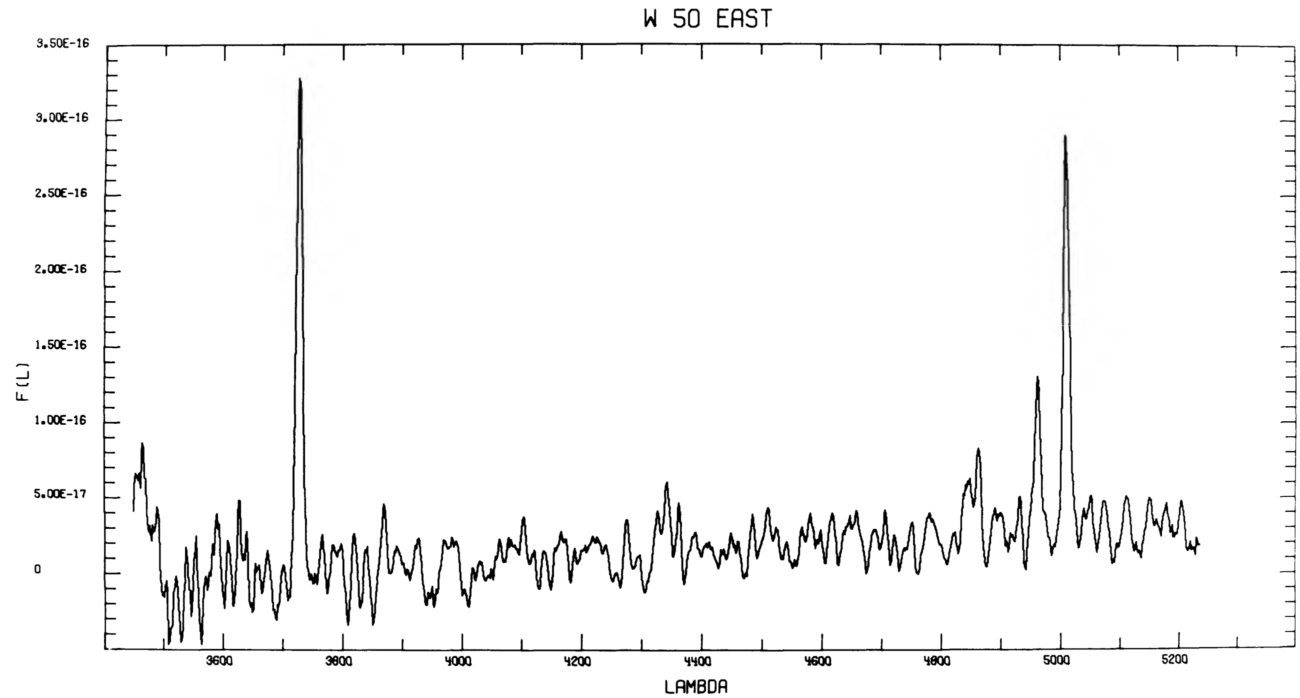

FIG. 1*a*

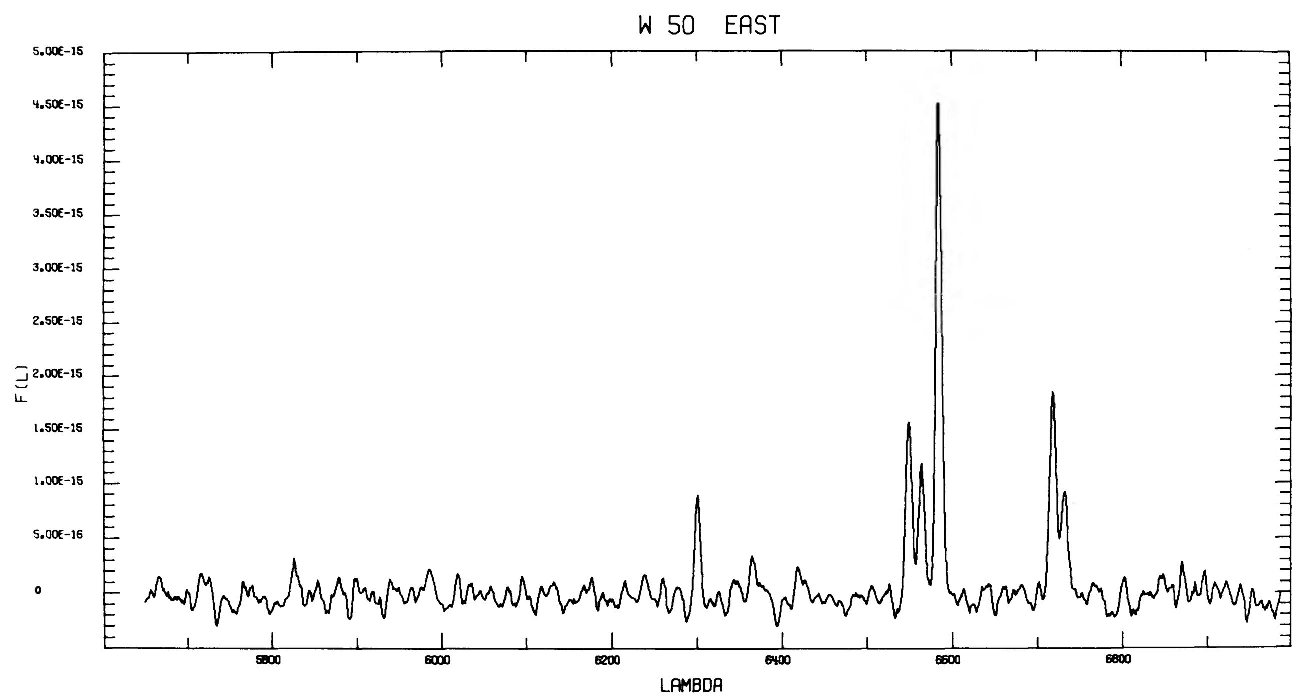

FIG. 1*b*

FIG. 1.—Flux density (ergs cm^{-2} s^{-1} $Å^{-1}$) vs. wavelength (Å) for W50: (*a*) blue spectrum of W50 East; (*b*) red spectrum of W50 East; (*c*) red spectrum of W50 West.

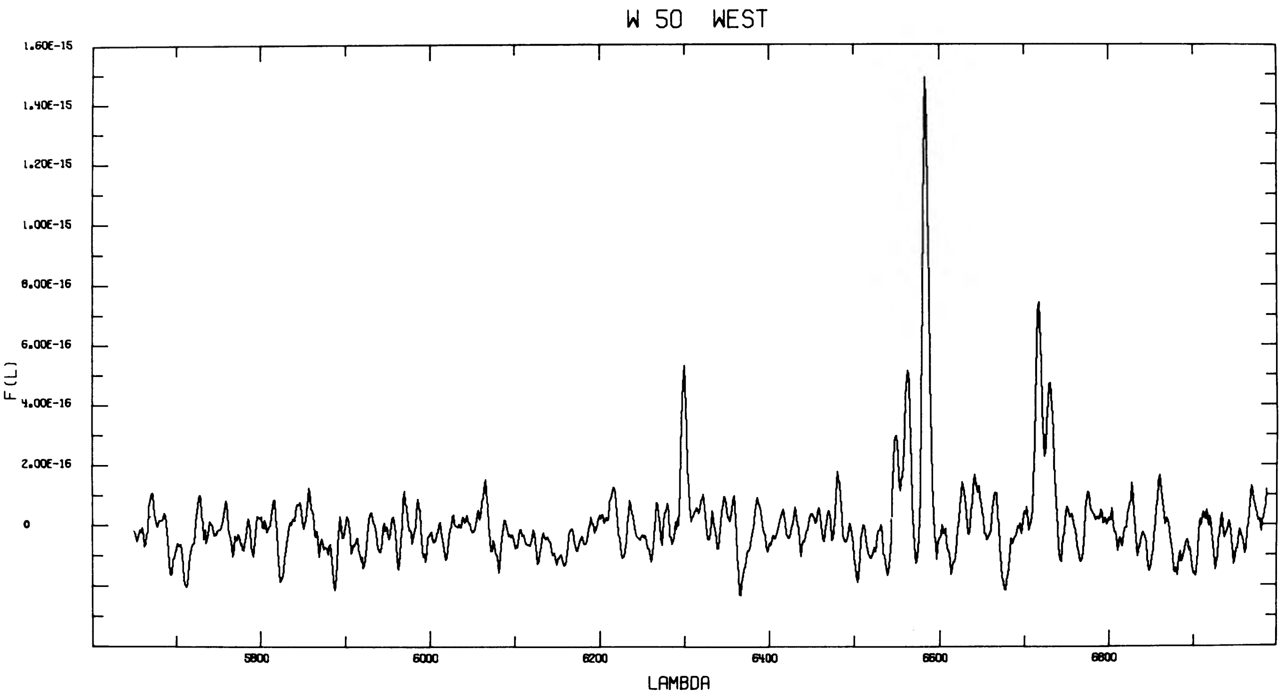

FIG. 1c

FIG. 1 (*Continued*)

TABLE 1

OBSERVATIONS OF W50

Parameter	W50 East	W50 East	W50 West
UT date................	1980 April 12	1980 April 11	1980 April 12
Spectral coverage (Å).....	5700–7000	3600–5200	5700–7000
Integration time (s).......	3600	6000	4800
R.A. (1950)..............	$19^h11^m49^s.4$	$19^h11^m49^s.4$	$19^h07^m09^s.1$
Decl. (1950)..............	$+04°57'38''$	$+04°57'38''$	$+04°57'05''$

It is likely, from the lower surface brightness in W50 West, that this area is more heavily obscured than W50 East, but this makes almost no difference to the relative line strengths in the observed region of the spectrum.

The line strengths reported here are in general accord with those of Murdin and Clark (1980), but the data appear to be of a much higher signal-to-noise ratio. In particular, the ratio of the [S II] 6717/6731 doublet is much better determined here. This line ratio is important in the interpretation of the data given in § III.

III. INTERPRETATION

The spectrum of W50 is generally like the spectrum of ordinary old supernova remnants like the Cygnus Loop (Miller 1974) and IC 443 (Fesen and Kirshner 1980). In particular, for W50 the ratio of [S II] 6717 + 6731/Hα is about 2, which is characteristic of shock-heated nebulae. It seems very likely that the nebulosity identified by van den Bergh is connected to the radio remnant W50.

The great strength of the [N II] lines is unusual, but not unique, among supernova remnants. In both W50 East and W50 West, we observed [N II] 6584/Hα of about 3, which is comparable to observations in the old SNR Puppis A (Dopita, Mathewson, and Ford 1977). This is usually interpreted as an abundance effect, but it is more likely to have its origin in the interstellar medium than in the supernova event that produced W50.

We observe the [S II] doublet ratio, $I(6717)/I(6731)$ is about 1.5–1.8. In the limit of low density ($n_e < 50$), the theoretical line ratio approaches 1.44 at $T_e = 10^4$ K (Pradhan 1976, 1978). The density in the region where sulfur is once ionized must be low, probably less than 100 cm^{-3}. At that density, the $I(6717)/I(6731)$ ratio should be about 1.35, which is the lowest value allowed by the data. This determination should be very insensitive to the flux calibration and to the reddening estimate. If we adopt $n_e < 100$, since the electron temperature is near 10^4 K in the zone where collisionally ionized sulfur is S^+, we can estimate the pressure in the gas. Calculations of cooling shock waves, such as those of Dopita (1977), Raymond (1979), and Shull and

TABLE 2

LINE STRENGTHS IN W50

		W50 East		W50 West	
Ion	λ	F^{a} (Hβ= 100)	I (A_v= 2.7)	F^{b} (Hα= 300)	I (A_v= 2.7)
[O II].......	3727	291	679	...	...
Hβ.........	4861	100	100	...	...
[O III]......	4959	109	101	...	...
[O III]......	5007	236	211	...	...
[O I]........	6300	480	202	782	316
Hα.........	6562	800	300	300	300
[N II].......	6584	2664	990	915	906
[S II].......	6717	1200	422	465	436
[S II].......	6731	664	232	315	294

[a] $F(\mathrm{H}\beta) = 1.5 \times 10^{-15}$ ergs cm^{-2} s^{-1}.

[b] $F(\mathrm{H}\alpha) = 1.2 \times 10^{-14}$ ergs cm^{-2} s^{-1}.

McKee (1979), show that the pressure at low temperatures is close to the pressure just behind the shock. A convenient relation is

$$n_0 V_7^2 = \frac{N(\text{S II})}{45}\,. \quad (1)$$

Here n_0 is the preshock density in the gas, V_7 is the shock velocity in units of 10^7 cm s^{-1}, and N(S II) is the density in the S$^+$ zone. We find $n_0\, V_7^2 \lesssim 2$ in these units.

We can use the ratio of [O II] 3727/[O III] 5007 as a sensitive measure of the temperature just behind the shock. For the value of 3 seen in W50 East, the shock velocity is probably near 90 km s^{-1} (Dopita 1977). Combining this with the pressure estimate from equation (1), we find that the preshock density of the gas we see must be less than 3 cm^{-3}. We might imagine that the regions we see are relatively dense interstellar clouds of density near 1 cm^{-3} embedded in an intercloud medium of density n. In that picture, developed for the Cygnus Loop by McKee and Cowie (1975), the blast-wave velocity in the intercloud medium would be 140 $n^{-1/2}$ km s^{-1}.

We can use our upper limit on the pressure in the filament to place a constraint on the total internal energy of W50. Following Chevalier (1974) and McKee and Cowie (1975) we write:

$$E = 2 \times 10^{46} \text{ ergs } \beta^{-1} n_0 V_7^2 R_{\rm pc}^3\,. \quad (2)$$

Here β is the ratio of the pressure in the blast wave to the pressure in the denser clouds where we measure the pressure. For W50, with an angular diameter of 1°, taking $\beta \approx 1.5$ and $n_0\, V_7^2 < 2$, we find:

$$E < 8 \times 10^{50} \text{ ergs} \left(\frac{D}{3.5 \text{ kpc}}\right)^3. \quad (3)$$

We note that this energy is no greater than the typical values associated with supernova remnants. As we discuss in § IV, this places constraints on the possible effect of SS 433 on W50.

IV. SPECULATION

Naturally we would like to use these observations of W50 to help establish or refute the link between W50 and SS 433 and to place useful constraints on the possible interactions between the present activity of SS 433 and the surrounding interstellar gas.

First, we consider the evolution of the W50 remnant on the assumption that it resulted from a single explosive event. If we assume that the Sedov solution is relevant, then we know:

$$R = 8.0 \text{ pc } E_{50}^{1/5} n_0^{-1/5} t_4^{2/5}\,, \quad (4)$$

where E_{50} is the initial energy in units of 10^{50} ergs, and t_4 is the age in units of 10^4 yr. Since we know the angular size of the remnant and a constraint on the energy from equation (3), we have:

$$t_4 > 11 n_0^{1/2} d\,, \quad (5)$$

where d, the distance, is in units of 3.5 kpc. On the other hand, assuming that the particle beams from SS 433 have sufficient energy to distort the shape of W50 and to create the "ears" in the overall radio contours implies an upper limit to the time scale $t_4 < 1 \times d$ (Begelman *et al.* 1980). Combining this with equation (5) yields $n_0 < 0.009$ cm^{-3}.

If SS 433 has had no influence on the remnant's evolution even though it is located inside the remnant, then the isotropic kinetic energy output from SS 433 is constrained by equations (3) and (5) to be less than:

$$\frac{E}{t} < 2 \times 10^{38} \text{ ergs}^{-1}\, d^2 n_0^{-1/2}\,. \quad (6)$$

Next, we consider the possible interaction of particle beams with the observed nebulosity. The optical filaments that we observe are close enough to the radio "ears" that it is worth considering whether they could be excited directly by the beams. The pressure in the beams, in the model of Begelman *et al.* (1980) is of order 8×10^{-9} cgs, which corresponds to $n_0\, V_7^2 \approx 5$. This is somewhat larger than the upper limit on the pressure we observe, indicating that the filaments we see may not be the result of direct impact of the beams on interstellar clouds.

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