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THE DISCOVERY OF OPTICAL EMISSION
FROM
THE SNR G 126.2 + 1.6

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ABSTRACT

We have used interference filter photographs to indentify an arc of nebulosity that is coincident with the radio contours of the galactic supernova remnant G 126.2 + 1.6. Spectrophotometry of the filament shows that the emission line spectrum matches the spectra of other galactic supernova remnants. In particular, the arc shows the usual strong [S II], and N II emission lines seen in other remnants and unusually strong [O III] emission as seen in a few remnants. The spectrum can be adequately matched by a shock of velocity near 100 km s^{-1} in an interstellar cloud of density 3. If the SNR is at a distance of 4.5 kpc as indicated by the radio Σ-D relation, then the observed pressure in the filament requires an initial energy near $4 \times 10^{51} \left(\frac{d}{4.5\ \mathrm{kpc}}\right)^3$ ergs.

Subject headings

nebulae: Supernova remnants
Interstellar: matter
Shock waves

I. INTRODUCTION

We present the first optical observations of the galactic supernova remnant (SNR) G 126.2 + 1.6 that was recently discovered with the Efflesburg 100 m radio telescope by Reich, Kallas, and Stube (1979; hereafter RKS).

In the radio, the remnant appears as a large (68 arc minute diameter) shell of emission with an exceptionally low surface brightness (Σ (408 MHz) $\simeq$ 12.2 x 10^{-22} watts m^{-2} Hz^{-1} $sterad^{-1}$) and a non-thermal spectrum (α = 0.85). We find that optical filaments in _An Emission Line Survey of the Milky Way_ by Parker, Gull, and Kirshner (1979) are coincident with the radio contours mapped by RKS at 1400 MHz and 2700 MHz. Further images and spectrophotometric measurements made at McGraw-Hill Observatory confirm the identification of the optical emission with the radio source, show that the optical spectrum of the filaments is that of a supernova remnant, and provide estimates of the physical conditions in the remnant.

II. OBSERVATIONS

a. Imagery

The region of the galactic plane near G 126.2 + 1.6 is included in _An Emission Line Survey of the Milky Way_ by Parker, Gull and Kirshner (1979). That work presents monochromatic images obtained through interference filters at [S II], Hα + [N II], [O III], Hβ and a blue continuum band at 4215 Å. The plates were obtained with a 300 mm focal length f/2.` Nikkor lens coupled with a Carnegie Image Tube. Each IIIa-J plate from the survey covers a seven degree field with about 30 arc second resolution.

The survey was done on a systematic grid with considerable overlap between fields. The region of G 126.2 + 1.6 is recorded on three separate sets of plates centered at 123 + 0, 128 + 0 and 125.5 + 5. An arc of emission nebulosity is easily visible on all three plates which recorded [O III] emission through a filter centered at 5010 Å, with a full width at half transmission of 28 Å. Figure 1 shows the best image of the [O III] emission, from the 128 + 0 field. In Figure 2 we show a sketch of the [O III] arc superposed on a portion of the 1410 MHz map of RKS. This arc, which extends about 12 arc minutes in the north-south direction has an apparent width of 2 arc minutes on these small-scale plates. The optical arc lies just outside the western radio rim of the remnant and is curved in the same way as the radio contours. This close correspondence between the optical and radio features is typical of the detailed connection seen at the periphery of most supernova remnants.

We also detect this arc of nebulosity in the light of Hα + [N II] as imaged through a filter centered at 6570 Å with a bandpass of 70 Å. Through our [S II] filter (at 6736 Å, $\Delta\lambda$ = 50 Å) the arc is at the very limit of detectability.

To improve the angular resolution of our images we employed the same [O III] filter with a 144 mm single-stage ITT image tube at the f/7.5 focus of the McGraw-Hill 1.3 m telescope. The interference filter has 130 mm of clear aperture so that nearly the whole field was used. The image tube has a fiber optic output which was recorded on baked IIa-D plates. Figure 3 shows that the arc of [O III] emission associated with G 126.2 + 1.6 is resolved into two filaments when photographed at an original plate scale of 22" mm^{-1}.

b. Spectroscopy

We employed the 2000-channel Intensified Reticon Spectrometer attached to the McGraw-Hill 1.3 m telescope to obtain spectrophotometry of the arc. The entrance aperture of the spectrometer measured 2.8" x 40" and was placed across the filaments as shown in Figure 3. Sky subraction was achieved by moving the telescope to a region of sky about 3^m west every 10 minutes. The spectrum was placed on a flux scale through measurements of standard stars, and corrected for atmospheric extinction based on a mean extinction table. The reduced spectrum shown in Figure 4 is the result of 60 minutes of integration on the filament.

In Table 1, we list the measured fluxes relative to Hβ, F(λ) and the fluxes corrected for interstellar extinction I(λ), with $A_V = 1.4$ as described below. For reference, we have also tabulated Miller's (1974) measurements of Position 3 in the Cygnus Loop and Fesen and Kirshner's (1980) measurements of G 65.5 + 0.5.

III. DISCUSSION

The spectroscopic data leave no doubt that the observed emission nebulosity is a supernova remnant. In particular, the line ratios of [N II] (λ6548 + λ6584)/Hα ≈ 1 and [S II] (λ6717 + λ6731)/Hα ≈ 1 correspond well to the ratios found for SNR's by Daltabuit, D'Odorico and Sabbadin (1976) and are distinctly different from the values usually measured in H II regions.

Despite the poor statistics at Hβ, the ratio [O III] (5007 + 4959)/Hβ is at least 10. This is a relatively large value but not unprecedented in the spectra of remnants, as shown by Miller's (1974) observations of the Cygnus Loop.

A large [O III]/Hβ ratio has been measured by Fesen and Kirshner (1980) in G 65.5 + 5.5, which is the other SNR which has been identified by the emission line survey described here (Gull, Kirshner and Parker, 1977). The emission line survey is much more sensitive to [O III] emission than the O-emulsions used for the blue plate of the Palomar Sky Survey, which may account, at least in part, for the strong [O III]/Hβ ratio in the remnants we have found. In particular, G 126.2 + 1.6 is easily visible in our [O III] plate, but not found by RKS on the blue Sky Survey print.

The uncertainties in all the lines in Table 1 are at least 20%, and the weak lines such as Hβ are even less precisely measured. Nevertheless we have made a rough estimate of the interstellar reddening to G 126.2 + 1.6 from the observed ratio of Hα to Hβ. If we assume that the emitted ratio is about 3 based on model calculations (Raymond 1979) then the observed value of 5.5 requires about 1.4 magnitudes of extinction at V if we employ the Whitford (1958) relation in the form given by Miller and Mathews (1972).

We can estimate some of the physical properties of the remnant by comparing the observations with detailed models of the emission from shock heated gas. In particular, by comparing the [O III]/Hβ strength with Raymond's shock models we find that the velocity of the shock through the gas we observe must be more than about 70 km s^{-1}. For slower shocks, the post-shock temperature is too low to produce strong [O III] emission.

As an example, we have listed Raymond's model X along with the observations. This model has a shock velocity of 100 km s^{-1} in a fully ionized medium with a very small magnetic field and initial density, n_c, of 10 cm^{-3}. The assumed abundances are those observed in the interstellar gas, in particular carbon and silicon are depleted relative to oxygen. The match is quite good for the limited selection of lines that we observe.

We can use the observed [S II] line ratio to infer the electron density at the temperature where sulfur is once ionized (about 8000 - 10,000 K). The observed ratio of [S II] λ6716/λ6731 is about 1.3, which corresponds to an electron density of n(S II) = 125 cm^{-3}, using Pradhan's (1978) cross sections! Roughly speaking, the pressure in the shock is constant so that the immediate post-shock pressure, $n_s T_s$ is about equal to the pressure in the zone emitting the sulfur lines where we know the temperature and density. The post-shock pressure is directly related to the density of the cloud, n_c, and the shock velocity which we take to be V_7 in units of 10^7 cm s^{-1}. Model calculations by Dopita (1977) and by Raymond show that

$$n_c \approx \frac{n(\mathrm{S\ II})}{45} V_7^{-2} \mathrm{cm}^{-3} \qquad (1)$$

For our case, $V_7 \sim 1$, n(S II) ~ 125, so the derived density is $n_c \approx 3$. This seems like a perfectly reasonable density for an interstellar cloud, and is consistent with the parameters for the shock model that we used for comparison.

We expect that the interstellar medium is clumpy so that the shock velocity in the intercloud medium can be substantially higher than 70 km s^{-1} (McKee and Cowie 1975). For example, if the average density for the intercloud medium is about 0.3 cm^{-3}, the shock velocity in that gas could be of order 200 km s^{-1}, and G 126 + 1.6 could be a galactic soft X-ray source. Inspection of HEAO -A data by Garmire (1980) did not reveal a source, but the absorption of soft X-rays by gas in the galaxy could be significant in this case. We can use our estimate of the pressure in the gas we see to estimate the initial energy of the supernova explosion. Following McKee and Cowie (1975) and Chevalier (1974) we write

$$E \approx 2 \times 10^{46} \ (\beta')^{-1} \ n_c \ V_7 \ R(pc)^3 \ \text{erg.} \qquad (2)$$

Here β' describes the coupling of the blast wave pressure to the cloud pressure. Using $n_c V_7^2 \simeq 3$ from (1) and adopting $\beta' \approx 1.5$, the angular diameter of 68 arc min from RKS, implies an initial energy

$$E \approx 4 \times 10^{49} \ D_{kpc}^{\ 3} \ \text{erg.} \qquad (3)$$

From the radio surface brightness, RKS estimate $D \approx 4.5$ kpc which requires an initial of 3.6×10^{51} erg. This number is large, but not excessive. For comparison, the same computation applied to the Cygnus Loop data in Table 1 gives (for $r \approx 20$ pc), $E \approx 7 \times 10^{50}$ erg.

The principal uncertainty in this energy estimate is the distance. A crude idea of the distance might be derived from the interstellar absorption along the line of sight, A_V [illegible] 1.1 mag. While this may seem small for a distance of 4.5 kpc, we find from integrating the 21 cm H I map by Westerhout (1973) that the total column density out to a velocity of -40 km/s which corresponds to a distance of 4.5 kpc, is $n_H = 3.4 \times 10^{21}$ cm^{-2}. Using the gas-to-dust ratio of 1.8×10^{21} atoms cm^{-2}mag^{-1} (Bohlin, Savage, and Drake 1978), this implies $A_V = 1.8$, which is consistent with the spectrophotometry.

In addition, Westerhout's survey shows a hole in the neutral hydrogen which corresponds to the angular size of the SNR in the direction of G 126.2 + 1.6. This local minimum in the hydrogen density is in the velocity range -40 to -55 km s^{-1} which is consistent with a distance of 4.5 kpc in a Schmidt galactic rotation model. If we imagine that the remnant has ionized the volume it contains then it seems plausible to associate this region with the remnant. On the other hand, this may be a mere coincidence.

We regard the distance to G 126.2 + 1.6 as uncertain - the radio Σ-D relation has very few SNR at the low-radio surface brightness measured by RKS, and even fewer for which an independent distance measurement is available. It will be extremely interesting to see if a 21 cm absorption line profile can be obtained for this source to improve the distance estimate.

IV. G 127.3 + 0.7

The SNR G 127.3 + 0.7 is also within the region mapped by RKS and photographed by us in our 128 + 0 field. Careful examination of our original plates shows no evidence for optical emission coincident with the radio contours of this remnant. We note that this remnant surrounds the point radio source G 127.1 + 0.5 which Caswell (1977) suggested might be radio emission from a collapsed stellar remnant. Optical observations by Kirshner and Chevalier (1978) show that the point radio source is associated with a distant radio galaxy rather than a galactic source. Caswell's observations of the extended SNR are consistent with a distance for this remnant of 3.0 or 5.7 kpc. This is in contrast to the view of Pauls (1977) who suggested that the SNR was physically associated with the open cluster NGC 559, which is at a distance of about 1.3 kpc(Lindhoff, 1969). Since the interstellar absorption to the open cluster is about $A_V \approx 1.35$, one might expect to see optical emission if the remnant is really at that distance. The fact that no optical emission is present favors the larger distance proposed by Caswell.

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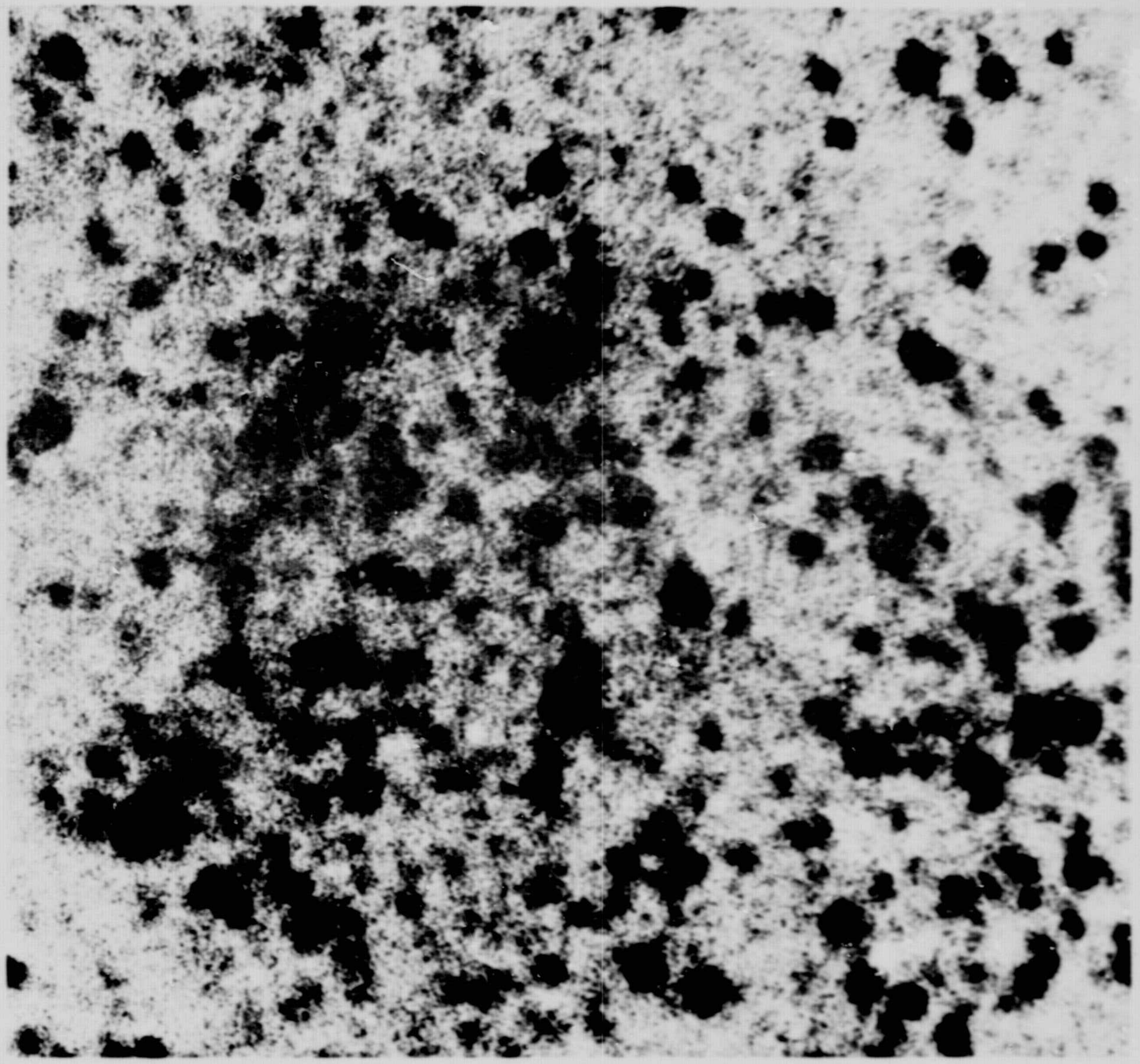

Figure 1. [O III] image of G126.2 + 1.6 as copied from the plate data as An Emission Line Survey of the Milky Way.

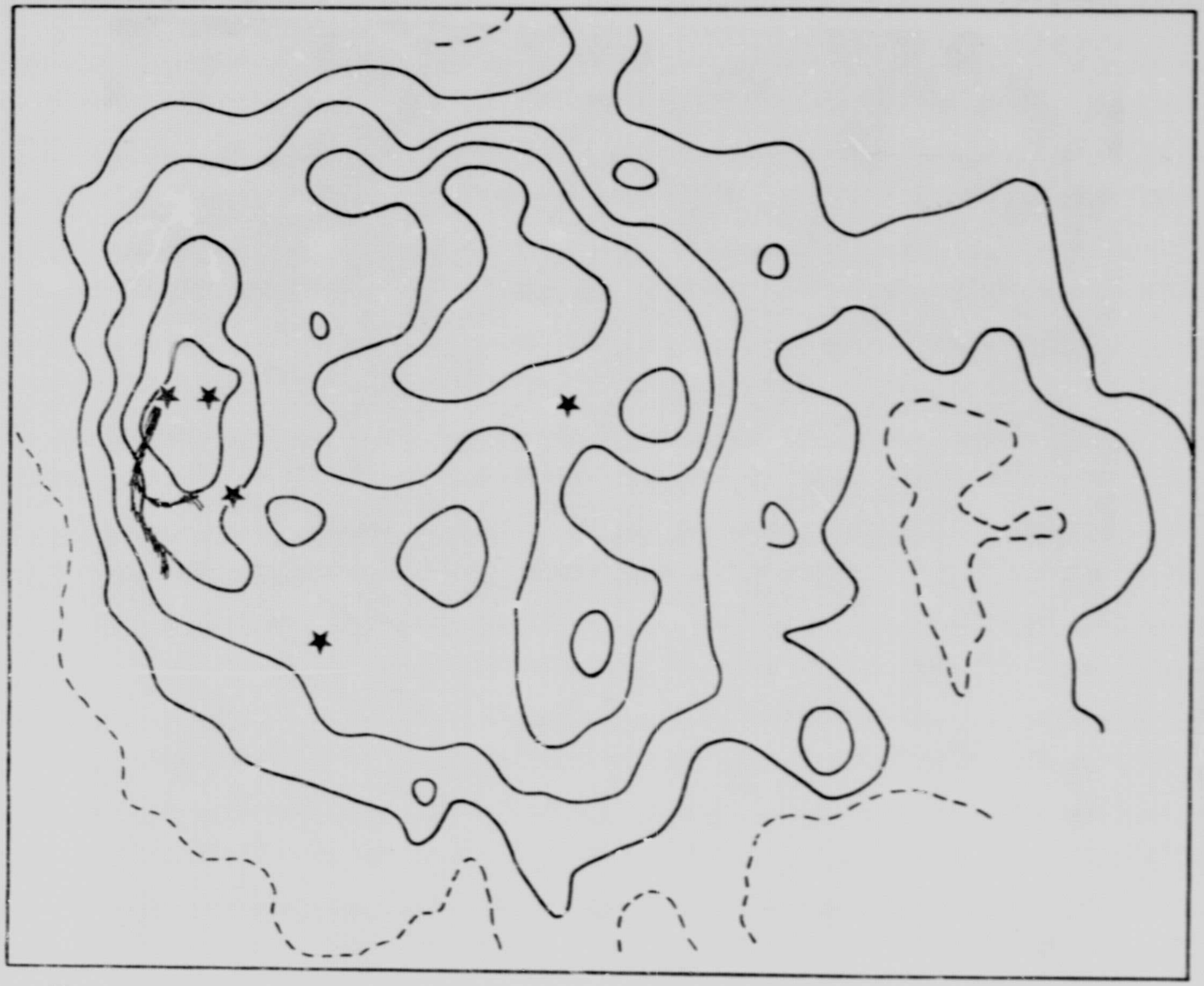

Figure 2. Sketch locating the [O III] filaments of Figure 1 with respect to the radio contours published by Reiche *et al.*, 1979.

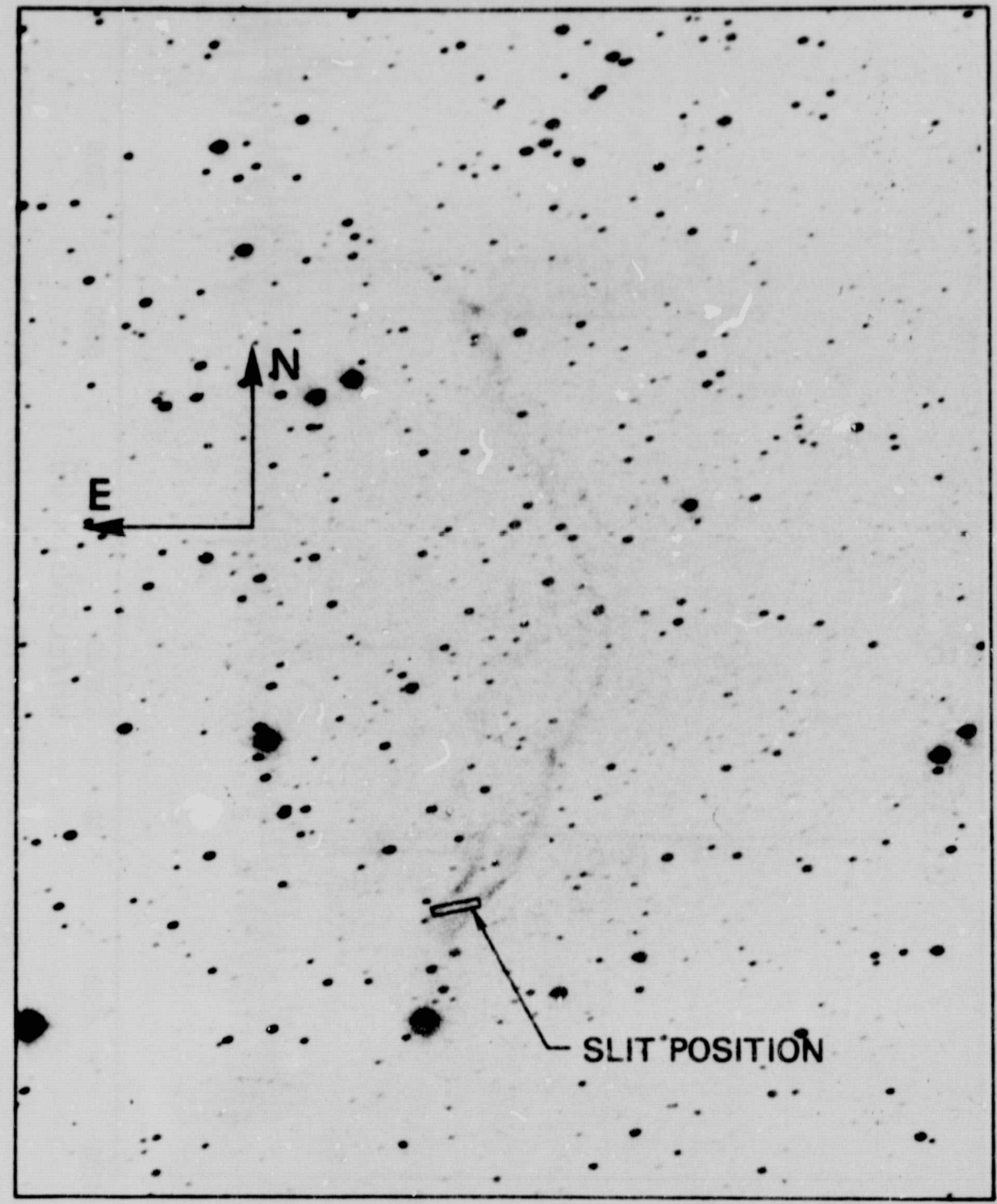

Figure 3. [O III] emission imaged by the McGraw-Hill 1.3 m telescope showing the slit location of the spectrum illustrated in Figure 4.

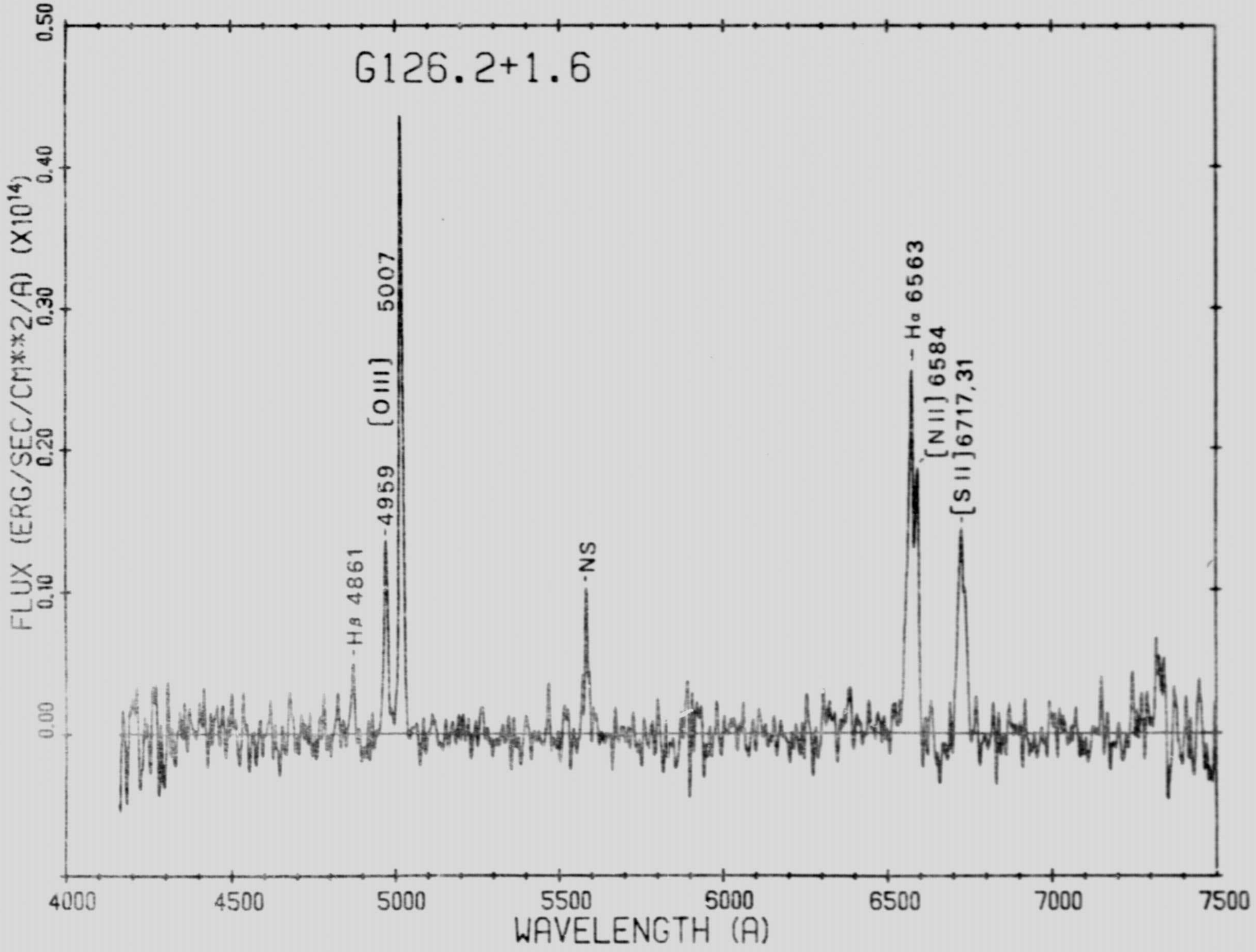

Figure 4. Spectrum of the [O III] filament associated with G126.2 + 1.6.

TABLE 1

Emission Lines in G 126.2 + 1.6

ION	λ	F (Hβ = 100)	I (A_V = 1.4)	Model[1] χ	Cygnus Loop[2] #3	G 65.5[3]
Hβ	4861	100	100	100	100	100
[O III]	4959 + 5007	1095	1031	881	1276	2447
[O I]	6300 + 6363	< 100	<60	50	29	-
[N II]	6548 + 6583	539	291	272	343	369
Hα	6562	554	300	308	306	250
[S II]	6716	339	177	155	130	250
[S II]	6731	254	133	126	114	240

1. Raymond (1979), 2. Miller (1974), 3. Fesen and Kirshner (1980)

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16. Abstract

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