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THE EXTRAORDINARY MASS-LOSS BUBBLE G2.4+1.4 AND ITS CENTRAL STAR

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ABSTRACT

We establish, by means of imaging and spectrophotometry that the nebula, G2.4+1.4, which in the past has been classified as a supernova remnant, is in fact a highly reddened, photoionized, mass-loss bubble of very high excitation powered by the most extreme Wolf-Rayet (WR) star of the oxygen sequence known. From Hα imaging we have established that the nebula is appreciably larger than previously suspected, with a diameter of 13′ in the N-S direction. At the distance of the nebula; 3 ± 1 kpc, this corresponds to a diameter of 11 ± 4 pc. The morphology of the nebula suggests that the wind from the WR star is driving into a dense cloud to the southeast. The central star, WR 102 or Sk 4, is shown to emit in lines of carbon and oxygen only and to be characterized by a stellar wind velocity of 5530 km s^{-1}. From a photoionization analysis of the surrounding nebula, this star was determined to have the following parameters;

$$\log (T_{\rm ion}) = 5.20 \pm 0.05; \quad \log (R/R_\odot) = 0.05 \pm 0.20; \quad \log (L/L_\odot) = 5.85 \pm 0.20 .$$

Although its current mass lies in the range 15–30 $M_\odot$, it must be a stripped carbon-oxygen core of a supermassive star ($M \leq 60\ M_\odot$) seen near the end of its life.

Subject headings: nebulae: H II regions — nebulae: individual (G2.4+1.4) — stars: Wolf-Rayet

I. INTRODUCTION

In an attempt to find optical counterparts for X-ray sources in Sagittarius, Blanco *et al.* (1968*a*) discovered an intense pointlike ultraviolet object which they identified with Sgr X-1 (GX 3+1). In a later publication, Blanco *et al.* (1968*b*), they also point out that the object is associated with a faint nebula $\sim 5'$ in diameter which is listed in the catalog of Lynds (1964). More accurate position of X-ray source excluded any possible association with the ultraviolet bright object, but this object itself has since turned out to be extremely interesting in its own right.

The ultraviolet object is a star now known variously as WR 102, Sk 4 or LSS/LS 4368 and is located at (epoch 1950.0) $17^{\rm h}42^{\rm m}40^{\rm s}.5$, $-26°09'20''$ or galactic coordinates $l = 20°.38$, $b = +1°.44$. A widened image-tube spectrogram of this star published by Freeman, Rodgers, and Lynga (1968) obtained on the 1.8 m telescope at Mount Stromlo, shows many very broad emission bands, with full width half-maximum widths ranging from 70 to 207 Å. These bands were identified with lines or blends of high-excitation elements He II, O III–VI, and C III–IV. There are no broad hydrogen lines in the spectra; narrow emission lines of hydrogen and of [O III] come from the associated nebula. From these spectral data Freeman *et al.* (1968) concluded that the ultraviolet object seems to be an extreme Wolf-Rayet star or, a possibility since excluded, a supernova. They indicate that all but one of the broad emission lines may be identified with blends of the usual high excitation lines of the stars of WC sequence (this one band is near 6049 Å). If the object is indeed a WR star, then an extrapolation of the line ratio and line width classification criteria would imply a classification of WC 4, that is to say, the most extreme example of the WC class known. These conclusions have been confirmed and extended by later workers and are further discussed in § III below.

In this paper, we present new data on the star and the surrounding nebula. We show that the star and the nebula are indeed associated, the nebula being a mass-loss bubble powered by the central star. We also derive, from photoionization modeling, the parameters of the central star. In a future paper, we will present dynamic data and detailed evolutionary and energetic estimates for the nebula.

II. THE NATURE OF WR 102

a) Classification

The stellar classification given by Freeman *et al.* (1968) WC 4 pec–WC 5 pec, has subsequently been broadly accepted (see, for example, van der Hucht *et al.* 1981 or Lundstrom and Stenholm 1979). Sanduleak (1971) listed five WR stars that were possibly of Population I and which show very strong O VI emission, two of them in the Magellanic Clouds. One of the three Galactic examples, Sk 3, has since been shown to be the central star of a very old PN (Barlow and Hummer 1982). According to modern understanding the remaining Sanduleak stars should be considered as a separate WO sequence, defined by the relative strengths of O IV, O V and O VI, and which represents the next evolutionary stage after the WC stage (Barlow and Hummer 1982). The small number of WO stars relative to WN and WC is explained if WO stage corresponds to stars that have reached the end of core He burning and are already burning C in the core. In order of increasing excitation, the WO sequence is Sk 2-Sk 1-Sk 5-Sk 4. Thus Sk 4 (WR 192) is the most extreme Population I WR star known.

We have obtained optical spectrophotometry in the range 3400–8200 Å using the coudé spectrograph with its 300 l mm^{-1} grating on the 1.8 m telescope at Mount Stromlo Observatory. The Photon-Counting Array (PCA) (Rodgers, Conroy, and Bloxham 1988*a*) was used as the detector. The data consisted of three separate spectra taken on 1988 August 1, 2, 11, and 14. Each observation covered only one-third of the

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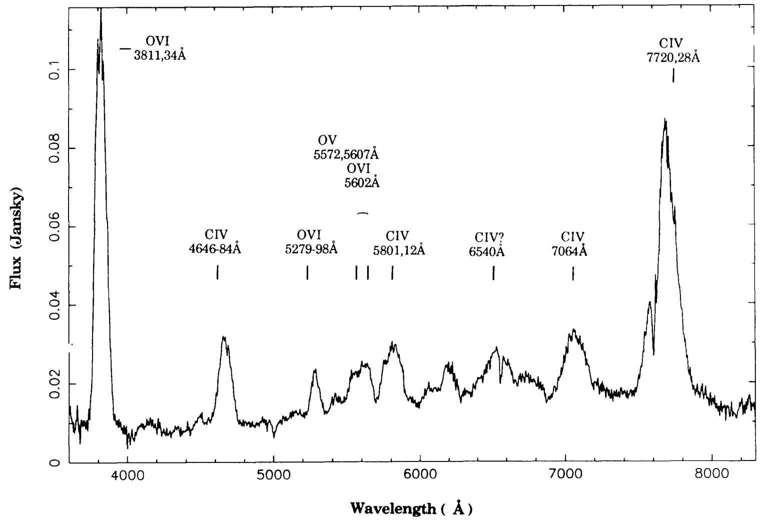

FIG. 1.—The optical spectrum of WR 102. The main emission features are identified in Table 1

full spectrum, and the grating was shifted between each exposure to obtain full spectra. These were merged and flux-calibrated against observed Oke (1974) standard white dwarfs using the FIGARO spectral reduction package.

The sum of the spectra so obtained is shown on Figure 1. This spectrum should be compared with the absolute optical spectrophotometry Sk 4 (WR 102) in the 3100–7400 Å range provided by Barlow and Hummer (1982) using the UCL IPCS system and RGO spectrograph on the AAT. The strongest spectral features are the O VI doublet at $\lambda\lambda$3811, 3834, the C IV (6–5) transitions in the range 4646–65 Å, the (3 $^2P^0$–3 ^2S) lines at 5801 and 5812 Å and the C IV blend of the (11–8) and (7–6) lines in the range 7400–7735 Å. Emission of C III is either very weak and completely absent and a weak feature at 6068 Å may even be due to O VIII. A weak feature at 6200 Å remains unidentified. The possibility of He II λ4686 being present, but blended with the C IV $\lambda\lambda$4646, 4658 doublet is entirely excluded by the absence of He I or He II emission in the IR (see below).

Infrared spectra in the range 1.0–2.5 μm were obtained at a resolution $R \sim 500$ on 1988 August 28 using the FIGS (Bailey *et al.* 1988) on the 3.9 m Anglo-Australian Telescope. The FIGS instrument (Fabry-Pérot Infrared Grating Spectrometer) is a cryogenic spectrometer with a 16 element linear array of discrete InSb photodiodes. The effective entrance aperture was 3".5 square, and a chopper throw of 20" N-S was used. The spectra were flux calibrated relative to the B8 IV star BS 6879 for which we adopt the broad-band magnitudes of Glass (1974). The absolute flux calibration should be good to $\pm 15\%$, this error being determined primarily by the relatively small aperture used. The wavelength scale is calibrated with respect to Earth atmospheric absorption features and should be accurate to better than 0.005 μm.

The near-IR spectrum of WR 102, shown in Figure 2, is dominated by strong broad emission lines of C IV superposed on a smooth continuum which is essentially flat in F_ν between 1.0 and 2.5 μm. The continuum is probably due to optically thick free-free emission in the ionized flow (Barlow and Hummer 1982). The principal emission lines in this type of star have been identified by Williams (1982) as those of C IV (8–7) 1.191 μm, C IV (9–8) 1.736 μm, and C IV (10–9) 2.427 μm. Lines of C IV (15–12) 2.278 μm, C V (10–9) 1.55 μm, and C IV (11–10) 2.11 μm may also be present. However, inspection of Grotrian diagrams shows that the C IV (8–7) transition is certainly blended with O VI (3 ^2D–3 $^2P^0$). The C IV (10–9) line is also a blend, with the C IV (13–11) line at 2.424 μm.

Note that there is no sign of either hydrogen or helium lines in this spectrum. In particular, note that the He I (2*s* ^1S–2*p* ^1P) transition at 2.058 μm and the He I (3*p*–4*s*) lines at 2.11 μm are completely absent in WR 102. In earlier, low-resolution spectra of WR stars, a feature appearing near this wavelength had been incorrectly identified as a He I feature and was thought to show that He I is generally well correlated with the C IV line strengths for the WC 5-WC 8 stars (Williams *et al.* 1980; Williams and Allen 1980). However, higher resolution work has demonstrated that this feature is in fact a blend of He I and the C IV (3*d*–3*p*) transition at 2.075 μm, with the C IV feature being the stronger in early WC stars (Lambert and Hinkle 1984). Thus, we can exclude the possibility of He I lines in the spectrum.

The possibility that He II lines may be present is not excluded by the optical data, since the 0.466 μm feature may be a blend of C IV with the He II line. However, the IR data show no sign of He II features. From the data of Hillier, Jones, and

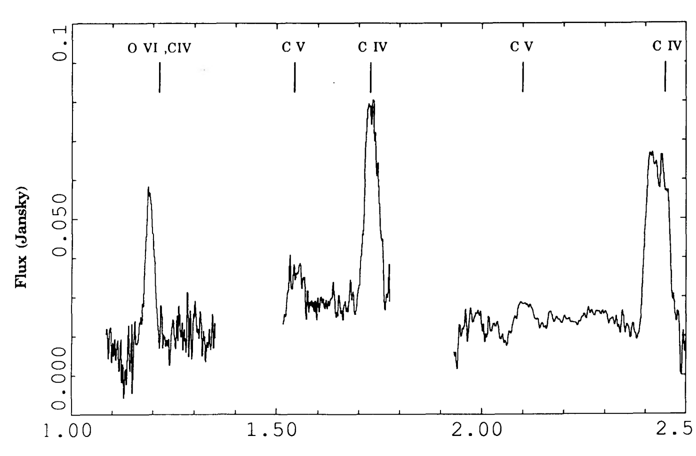

FIG. 2.—The IR spectrum of WR 102 between 1.1 and 2.5 μm. The features are identified in Table 1.

Hyland (1983) on HD 50896, we would expect the strongest He II lines which are not themselves involved in blends with He I to be found at 1.165 μm (a blend of the (7–5) and (11–6) transitions), at 1.27–1.29 μm (a blend of the (20–7), (19–7), and (10–6) transitions), at 2.037 μm (the (15–8) transition), at 2.164 μm (the (14–8) transition), and at 2.31–2.37 μm (a blend of the (20–9), (19–9), and (13–8) transitions). Inspection of Figure 2 reveals that none of these features appears, except when involved in a blend with highly ionized carbon or oxygen transitions. In these cases, the measured wavelength of the centroid of the line agrees better with the wavelength of the heavy element transition.

These data give the most unequivocal evidence that the He-rich layers of this star have been completely stripped off and that here we are seeing the bare He-burnt core of a massive star.

The stellar wind velocities may be estimated from the line widths at zero maximum (FWZM), since almost all of these lines have the parabolic, or Gaussian, profile expected for an optically thick wind (an optically thin wind would give a flat-topped profile). The identifications, wavelengths, and line widths at half-maximum and at zero maximum are given in Table 1. The stellar wind velocity inferred from the FWZM of the unblended or very closely separated lines in this table yields $V_w = 5530(\pm 200)$ km s^{-1}. This compares with the value of $V_w = 5500$ km s^{-1} determined by Barlow and Hummer (1982) from the FWZM of the O VI λ3811, 34 line and a velocity of 5700 km s^{-1} estimated by Torres, Conti, and Massey (1986) from the relation between line width and excitation potential of the upper level by extrapolating the observed line widths to zero excitation potential. This procedure is liable to give a better estimate of the maximum wind velocity, since low-excitation lines are formed farther out in the wind (Schmutz and Hamann 1986; Hillier 1987, 1988) and therefore will tend to have a higher velocity width. On the basis of the similarity between these various estimates of the wind velocity, it would appear that there is little or no variability in the velocity of the outflow.

At a velocity of 5530 km s^{-1}, each solar mass lost carries an energy of 3×10^{50} ergs to the interstellar medium (ISM). This magnitude of this energy shows that mass loss from the central star may have already delivered a momentum to the ISM which is greater than that of a supernova, since, for an equivalent energy input, mass loss couples better to the ISM than a point explosion.

Several observations which suggest that WR 102 is a variable have been published in the literature. Johnson and Golson (1968) and Johnson (1970) have found a nonrandom variability of $\sim 0^{\mathrm{m}}.3$ in passbands of equivalent width 109 Å and 180 Å centered about Hβ, and a larger and more irregular variability in filters of narrow passbands (equivalent width ~ 20 Å, centered at 4648, 4684, and 4865 Å. The time scale of this variability is ~ 1 hr. Since these passbands effectively measure the C IV line, and the nearby continuum, these observations are suggestive of an emission line variability.

Five-color Walraven photometry WR 102 was provided by van Genderen (1974). From a total of 26 observations spanning 1971 May–September, he concluded that the star seems to show a long time scale (~ 3 month) variation in the V and B passbands with a total amplitude of $0^{\mathrm{m}}.1$. The mean deviation in one point with respect to the average curve is $\sim 0^{\mathrm{m}}.05$. Van Genderen remarked that in Johnson's U-range short time variations was much smaller, which might indicate that O VI lines are more stable than the other emission line features in B and V.

Our spectrophotometry is difficult to calibrate on an absolute scale, but it is clear that the relative strengths of lines, and lines with respect to the continuum showed no significant variability over the period of time covered by our observations. It is possible that the variability reported by others represents instabilities or irregularities in the outflow, but for the moment this question must be left open.

TABLE 1

IDENTIFICATIONS AND OBSERVED WIDTHS OF STRONG EMISSION FEATURES IN WR 102

Measured Wavelength λ (μm)	Line Identification: Ion and Transition	Line Identification: λ (μm)	FWHM (km s^{-1})	FWZI (km s^{-1})
0.3820	O VI (5 $^2P^0$–5 ^2S)	0.3811 0.3834	7625	11,760
0.4660	C IV (6 ^2G–5 $^2F^0$) C IV (6 $^2F^0$–5 ^2D) C IV (8 ^2G–6 $^2F^0$)	0.4646 0.4658 0.4685	7091	11,608
0.5805	C IV (3 $^2P^0$–6 $^2F^0$)	0.5801 0.5812	7100	10,590
0.7050	C IV (9–7)	0.7064	7110	10,604
0.7730	C IV (7–6) C IV (11–8)	0.7726–0.7730 0.7720	5822	13,390
1.191	O VI (3 ^2D–3 ^2P) C IV (8–7)	1.175, 1.189 1.192	5870	10,840
1.55	C V (10–9)	1.55	7900	...
1.730	C IV (8–7)	1.736	6180	11,900
2.106	C V (11–10)	2.11	6350	...
2.429	C IV (10–9) C IV (13–11)	2.427 2.424	7890	11,190

III. OBSERVATIONS OF G2.4+1.4

a) Hα *Imaging*

The size of G2.4+1.4 was thought to be ∼5′ (e.g., Johnson 1975). However, narrow band interference filter photographs taken by Treffers and Chu (1982) with the image tube camera (CITD) on the Kitt Peak 91 cm telescope show that an inner, highly symmetrical filamentary shell, 5′ in diameter, is embedded in a larger shell-like structure extending ∼8′ in the NE-SW direction. A curious feature of the nebular morphology was revealed by this work, namely, that the WO star appeared to be displaced from the center of its ring of filaments, toward the NE boundary. It was difficult to see how this could be the case given the short period of time the star exists as a WR star. A density gradient may exist, but evidence based on the surface brightness and extent of the filaments would suggest that the density was larger toward the SW, opposite to what would be required to explain the position of the central star. There remain two possible explanations. Either the central star has a high proper motion toward the NW or else that the filaments in the blow-out direction are so faint as to be undetected in earlier work.

This last explanation appears to be the correct one, since we discovered very extensive high-velocity gas emitting in [O III] in the NW quadrant (described in a following paper; Dopita and Lozinskaya 1990). Following this, we performed deep Hα imaging to attempt to determine the full extent of the nebula. We used a three-cycle interference filter 90 mm in diameter, with a peak transmission of 55% at 6565 Å, and with a 55 Å FWHM. This was placed in the f/18 beam of the 2.3 m telescope at Siding Spring, and the red arm of the double-beam spectrograph (Rodgers *et al.* 1988*a*), was used as a focal reducer, the grating being replaced by a mirror for this exercise. The detector was a Photon Counting Array (PCA) with a GaAs image tube front stage, giving a Q.E. close to 20% (Rodgers *et al.* 1988*b*). The system acted as an f/1.5 camera with a scale at the focal plane of 1″.0 pixel^{-1}. From nine pointings in nonphotometric conditions on the nights of 1988 September 8 and 9, we were able to image virtually all the nebula with adequate overlap. Distortion across the field of 5′.8 proved to be less than 1 pixel, so that the image was reconstructed by flat-fielding individual frames, performing astrometry of stars to determine relative field positions, renormalization of the individual frames to a common intensity scale, and finally, a cutout of portions of these frames into a composite image. After reconstruction, the data were Hanning smoothed in both *x* and *y* directions, and then rebinned to give pixels 1″.37 square on the sky. All reductions were performed with the PANDORA software package at Mount Stromlo.

The resultant image is shown in Figure 3 on a logarithmic intensity scale, in order to better bring out the fainter features. The nebula is revealed to be appreciably larger than hitherto supposed, with a complex double shell structure extending over some 13′, much further to the north and to the west than previously recognized. These outer portions are scalloped in a semiregular pattern ∼3′ in diameter, suggestive of the operation of a large-scale instability. It is possible that the "superwind" generated during the very short-lived WO stage has punched holes through the shell generated in the earlier WR phases, but this would imply very large motions in the filaments to the NW. This point will be developed in a following paper which presents the dynamical data and discusses these energetic considerations in detail.

The central star first appeared to be displaced to the western side of the nebula in the earlier observations. However, this now appears to be the result of the higher surface brightness of the nebula to the SE. The reason for this is that the nebula is confined by a dense cloud on this side, which appears as diffuse emission on our Hα image, and as an incomplete ring of hot dust in the IRAS 60 μm image (Graham 1985). With respect to the extended filamentary shell, the central star now appears somewhat closer to the brighter easterly boundary of the nebula.

b) Spectrophotometry

Spectrophotometry in four long slit positions each extending across some 6′ of the nebula were obtained on the nights of 1988 July 19–20 and of July 20–21. The exposure times were 3000 s per slit, except for the fourth slit position, which was cut short by cloud after 1400 s effective exposure. The instrument used was the double-beam spectrograph on the 2.3 m telescope at Siding Spring with its 300 l mm^{-1} gratings. With a dichroic beamsplitter cutting at 5500 Å, this gave complete spectral coverage from 3400–7800 Å. The detector was the 2CCD Photon Counting Array (Rodgers *et al.* 1988*a*). Since the data fell on four different CCDs, these each had to be reduced separately and then combined into a single spectrum. The reduction process consisted of flat fielding, data extraction, wavelength linearization, sky subtraction, reduction to flux, merging of CCDs, and summing of rows to extract spectra of individual filaments. The data was all reduced using the PANDORA software package. The primary flux standard star used was V Ma 2 (Oke 1974).

In Figures 4*a*–4*b*, a portion of the resultant sky-subtracted spectrum in slit position 2 is shown. It is evident that the degree of excitation varies considerably along the slit, in particular in the low-excitation species such as [N II] and [S II], which are enhanced considerably in their relative intensities in the vicinity of the fine filaments. This is consistent with the narrow-band imaging results of Treffers and Chu (1982) who found that the morphology of the nebula is very similar in Hα and [O III] lines, whereas the appearance in the [N II] and [S II] lines is quite different.

From these four slit positions, the spectra of the 10 brightest filaments were extracted. The positions, orientations, and sizes of the extracted filaments are given in Table 2, and the relative intensities of the brightest lines in Table 3.

The data from the brightest of these filaments, S2-2, and

TABLE 2

SLIT POSITIONS AND SIZES FOR INDIVIDUAL FILAMENTS IN G2.4+1.4

Slit Identification	Slit P.A.	Slit Length	Slit Center Position (Epoch 1950.0)	
S1-1	90°	14′	17′42″39″.0	−26°09′00″
S1-2	90	31	17 42 48.0	−26 09 00
S2-1	90	5	17 42 41.5	−26 08 15
S2-2	90	5	17 42 44.2	−26 08 15
S2-3	90	16	17 42 48.0	−26 08 15
S2-4	90	13	17 42 51.5	−26 08 15
S3-1	50	11	17 42 48.5	−26 12 10
S3-2	50	10	17 42 46.0	−26 09 30
S3-3	50	11	17 42 41.0	−26 08 20
S4-1A[a]	0	14	17 42 37.5	−26 08 30
S4-1B	0	12	17 42 37.5	−26 09 15

[a] Because of the weakness of the signal, these two slit positions were co-added for analysis.

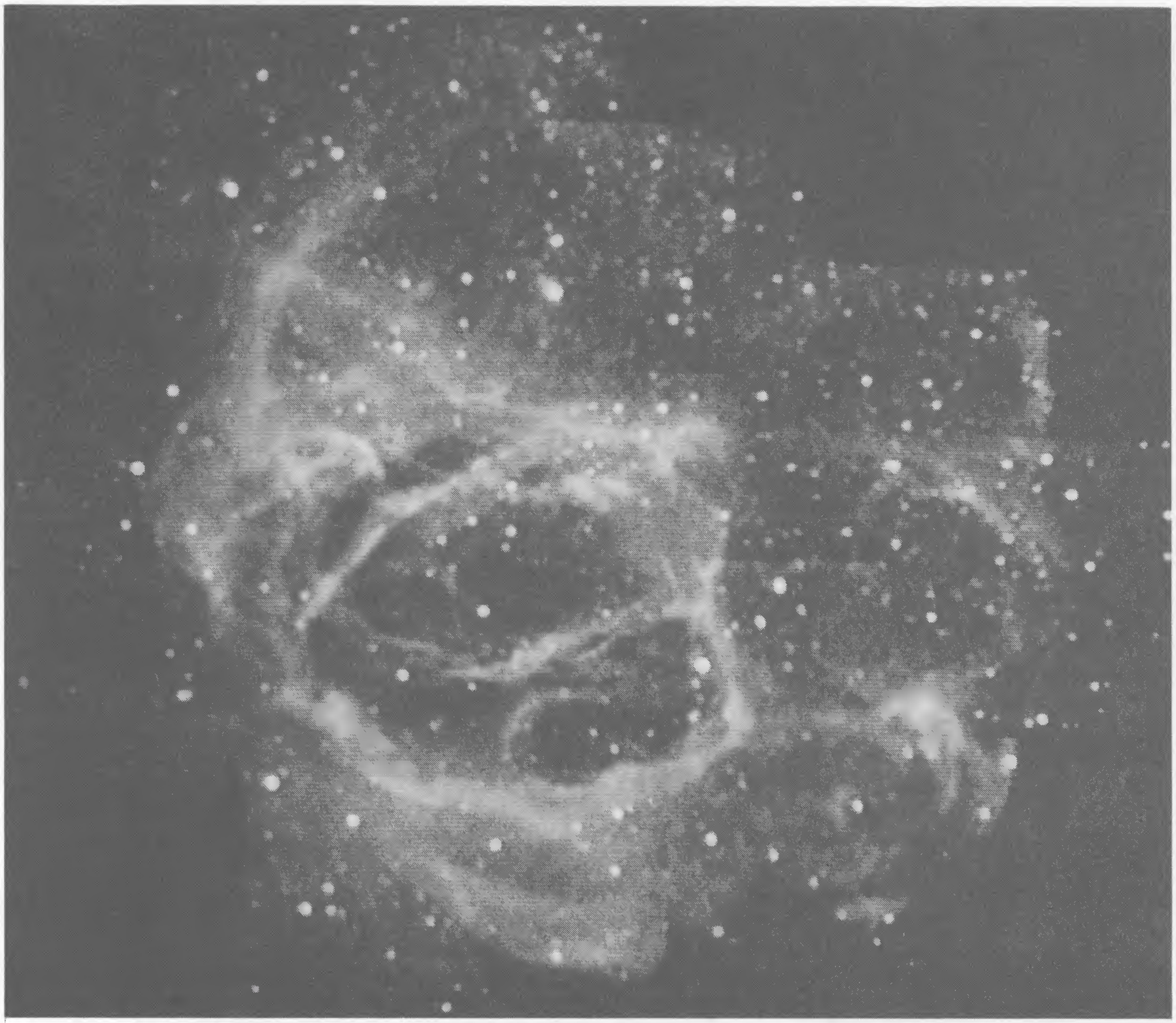

FIG. 3.—The composite Hα image of G2.4+1.4. North is at the top, east to the left. Note the curious scalloped appearance of the nebula in the newly discovered portion to the north and the west. The full extent of the nebula is yet to be ascertained. The exciting star is the bright, nebular embedded star at the northern apex of the V-shaped asterism just above the center of the image.

S2-2, S2-3, and S2-4, were co-added to optimize the detection of faint lines. The complete line fluxes of the resultant spectrum is given in Table 4, and the spectrum itself is illustrated in Figure 5. The spectrum is very similar to a planetary nebula of excitation class 7.5, as has already been noted by Johnson (1976).

c) *The Reddening and Distance of the Star and Nebula*

For the exciting star, Barlow and Hummer (1982) have estimated *UBV* magnitudes and reddening from their spectrophotometry of the continuum flux level. (These magnitudes are thus fainter than the *U*, *B*, and *V* derived from the filter photo-

TABLE 3

RELATIVE LINE FLUXES IN INDIVIDUAL FILAMENTS OF G2.4+1.4

	RELATIVE LINE FLUXES WITH RESPECT TO Hβ = 100.0									
ION	S1-1	S1-2	S2-1	S2-2	S2-3	S2-4	S3-1	S3-2	S3-3	S4-1[a]
He II λ4686	26	30	70	50	52	54	>15	41	37	91
Hβ λ4861	100	100	100	100	100	100	100	100	100	100
[O III] λ4959	180	201	107	265	140	160	160	182	300	130
[O III] λ5007	525	680	360	750	480	500	450	480	880	440
[N II] λ6548	20	89	34	128	29	8	84	80	125	35
Hα λ6563	945	1280	730	1390	930	540	1040	885	1050	780
[N II] λ6584	58	260	102	303	100	33	235	193	378	109
[S II] λ6717	17	100	68	284	41	23	164	74	214	67
[S II] λ6731	14	80	51	252	24	13	110	53	130	45

[a] The ratio of the red to blue lines may be somewhat underestimated for this position.

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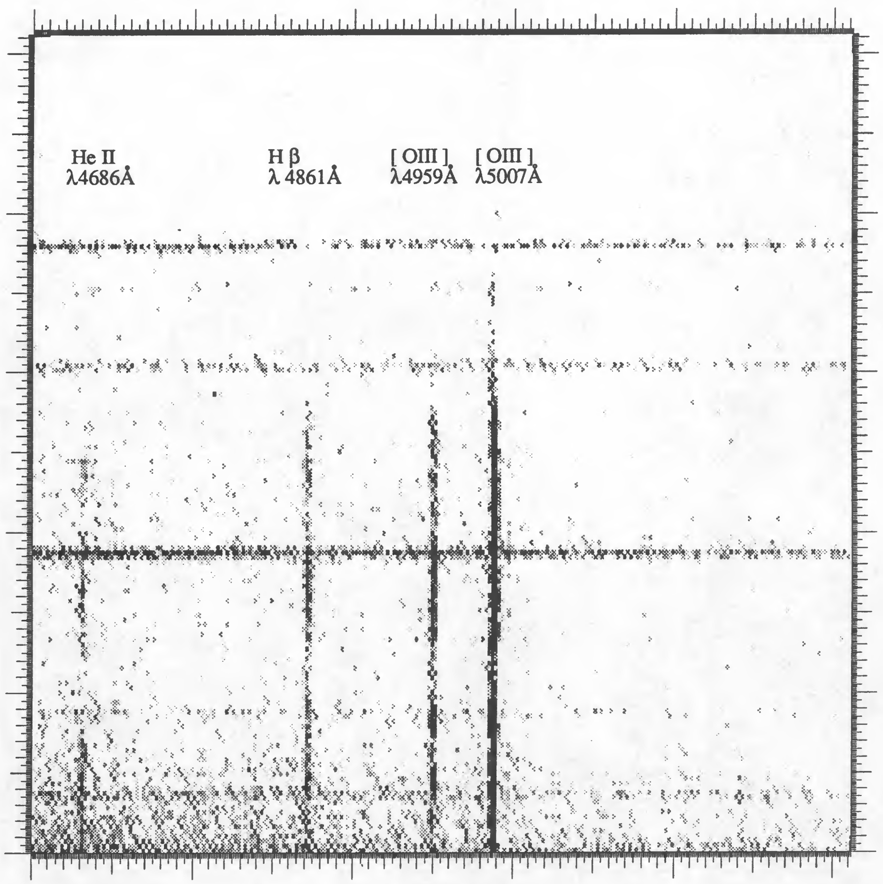

FIG. 4*a*

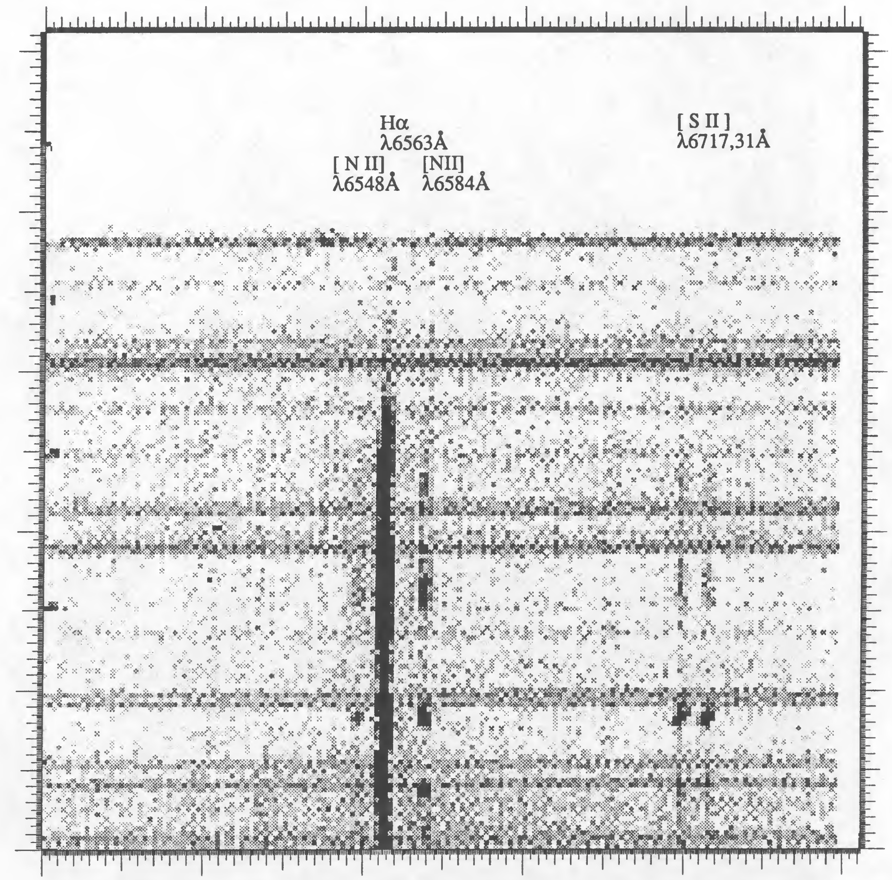

FIG. 4*b*

FIG. 4.—The sky-subtracted spectrum in slit position S-2. (*a*) In the region of He II λ4686–[O III] λ5007. (*b*) In the region of [O I] λ6300–[S II] λ6731. Note the large filament-filament changes in excitation.

TABLE 4

FILAMENT-AVERAGED SPECTRUM OF G2.4+1.4

Ion	Line Flux with Respect to Hβ = 100.0	
	Observed	Corrected
[O II] λ3728	18:	55:
Hδ λ4100	<7	>14[a]
Hγ λ4340	15:	>24[a]
He II λ4686	44	55
Hβ λ4861	100	100
[O III] λ4959	170	157
[O III] λ5007	532	472
He I λ5876	11:	5:
[O I] λ6300	30:	11:
[O I] λ6363	14:	5:
[N II] λ6548	51	15
Hα λ6563	924	272
[N II] λ6584	147	43
He I λ6678	16	4
[S II] λ6717	72	19
[S II] λ6731	60	16
[Ar III] λ7165	104	23
[O II] λλ7318, 7330	20:	4:

[a] Uncertain for reasons given in the text.

metry, since strong emission lines are included in the latter). To obtain A_v, an intrinsic $(B-V)_0 = -0.32$ and $R = 3.1$ was assumed. This gave $A_v = 5.1$ mag. for the central star.

It is evident from Table 4 that the nebula has a peculiar Balmer decrement, since Hγ is hardly seen, and the Hδ and higher members of the Balmer series are absent. The logarithmic reddening constant derived from the Hα/Hβ ratio is 1.6 ± 0.2, if the ratio is near its case B value. If, on the other hand, the ratio of Hβ/Hγ were to be used, a value of order 3.7 would be inferred. However, it is certain that this latter value is incorrect, since the nebular spectra are contaminated by a faint continuum, which is the result of faint stars lying on the slit, or dust scattered starlight. The result of this will be to lose the higher members of the Balmer series in the stellar absorption features, and so steepen the Balmer decrement. It is also possible that this direction is characterized by an unusual size distribution of grains. Larger grains would give a steeper UV

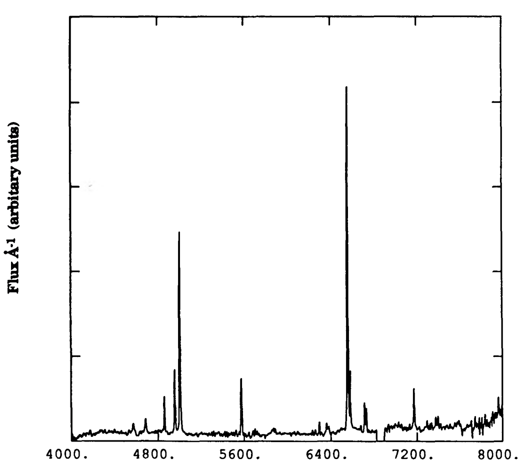

FIG. 5.—The "filament average" spectrum of G2.4+1.4. This is similar to a planetary nebula of excitation class 7.5.

extinction, which would tend to further weaken the higher members of the Balmer series. We therefore adopt a mean nebular logarithmic reddening constant of 1.6, which corresponds to a $A_v \sim 3.5$ mag.

If WR 102 is similar to the WO stars in the Magellanic Clouds, then the absolute magnitude is of order $M_V \sim (-4$ to $-5)$. The continuum V magnitude of 14.6 given by Barlow and Hummer (1982), combined with a reddening of 4.3 ± 0.8 mag then implies a distance of order 3.0 ± 1.0 kpc and a nebular diameter of 11 ± 4 pc.

IV. THE NATURE OF G2.4+1.4

a) The Excitation Mechanism

The properties of a radiosource found within 2′ of the peculiar Wolf-Rayet star was first discussed by Goss and Shaver (1968). They mapped the region at 5000 MHz using the Parkes radio telescope and presented evidence to show that the source is extended (5.′7 in R.A. × 9.′2 in Decl.) with a mean emission measure of 4.8×10^3 pc cm^{-6}, and that the continuum spectrum of the source appears to be thermal.

The nebula G2.4+1.4 was later regarded to be a SNR following arguments that the nebula has a nonthermal radio spectrum, even though the nebula would seem to be subluminous and the WR star was recognized as a possible source of excitation (Johnson 1973, 1975; Treffers and Chu 1982; Chu, Treffers, and Kwitter 1983). However the alternative interpretation, that G2.4 + 1.4 is a wind-blown bubble around the WO star, has also been considered (Chu *et al.* 1983; Green and Downes 1987). Up to the present time, neither a SNR nor a wind-blown bubble fits all the observational data completely, and as a result compound mechanisms, like old SNRs with the WO star as a source of photoexcitation, wind-blown bubble with unusual nonthermal radio emission, have been discussed.

The conclusion by Johnson (1973, 1975) that the continuum radio emission of the nebula is nonthermal is so far the key and the only direct argument in support of a SNR identification. Johnson's conclusion that the radio emission was nonthermal was based mainly on the low flux density which he measured at 15.5 and 31.4 GHz; see his Figure 2. Although nobody has since repeated measurements at these high frequencies, Caswell and Haynes (1987) and Green and Downes (1987) have given some indirect arguments, based on their low-frequency continuum measurements and on the data of Reich *et al.* (1984), that the radio spectrum of G2.4+1.4 is at present uncertain and could well be thermal. Green and Downes (1987) observed the nebula at 4.86 GHz with a resolution of 11 × 31 arcsec^2. These high-resolution data reveal a thin-filamentary radio structure which is very strongly correlated, both in position and intensity, with the optical emission in the Hα and [O III] lines. This is circumstantial evidence for a thermal excitation of the radio emission. No significant linear polarization was detected, an upper limit of ~5% for polarization of the brightest part of the nebula G2.4+1.4. This constraint on polarization does not rule out the possibility of a nonthermal mechanism, since interstellar depolarization is likely to be very significant because of large reddening.

A more serious objection to the nonthermal emission hypothesis is raised by the observations of Caswell and Haynes (1987) who found weak, broad (FWHM = 53 km s^{-1}) H109α and H110α radio recombination lines in the nebula. This is a clear indication that the radio emission seen at 5 GHz is indeed thermal. Furthermore, the recombination line velocities

($V_{LSR} = +3$ km s^{-1}) are in good agreement with the optical data, to be presented in a subsequent paper (Dopita and Lozinskaya 1990).

The optical spectrophotometry provides a strong constraint on the mode of excitation of the nebula. If it were shock excited, then shock models (e.g., Dopita *et al.* 1984) show that the [S II] lines and the [N II] lines would be comparable in strength with the Hα recombination line. Furthermore, these forbidden lines should be well correlated, both in position and intensity, with the Hα emission, since both arise in the recombination zone of the shock. This is inconsistent with both our observations, presented in § IV, above, and with the narrow-band imaging observations of Treffers and Chu (1982), who likewise concluded that the morphology of the nebula is inconsistent with the shock excitation hypothesis.

Another objection to the shock-excitation hypothesis is raised by the relative strength of the He II λ4686 line. In shocks of high velocity, the ratio He II/Hβ is set by the respective recombination rates and the relative abundances of He and H. The observed He II line would imply a strong overabundance of He in the ionized material. However, this cannot be excluded *a priori*, especially when one considers the extreme nature of the central star.

The weakness of the [S II] and [N II] lines also tend to suggest that the nebula is photoionized, rather than shock-ionized, since in shock-excited regions these are strong or even comparable to Hα. Finally, the observation of a strong [Ar III] line makes it almost inconceivable that the nebula is shock excited. This line is normally emitted in a high-temperature zone in shocks, and as a consequence, the line is always very weak compared with that found in photoionized plasmas.

From these arguments we conclude that the nebula is a wind-blown bubble which is radiatively excited by the strong UV radiation of WO star, and that the diffuse [N II]-strong filaments in the SE, having no Hα and [O III] counterparts, most probably delineate an ionization front in a denser cloud. The material to the NW is clearly much more tenuous and is therefore exposed to harder ionizing radiation which converts N^+ and S^+ to higher ionization states (Treffers and Chu 1982).

b) Photoionization Models

We have constructed photoionization models using the general-purpose code MAPPINGS (Binnette, Dopita, and Tuohy 1985). The observational material obtained in this paper, combined with that already published puts very useful constraints on the allowable parameters for the models and on the nature of the photoionizing source. The ratio of the [S II] lines suggests a density of ~100–150 cm^{-3}, which we have assumed. Since the nebula is clearly filamentary, and is compressed by the hot shocked stellar wind gas of WR 102, it is safe to assume that isobaric conditions apply throughout the nebula and that the ionized material forms a thin shell.

The Hα observations presented here suggest that the relative thickness of the ionized material is small, $\Delta R/R \sim 0.1$, or even less. Another estimate can be derived from the observations of Goss and Shaver (1968). Assuming that the emission at 5000 MHz is of thermal origin, they estimated an emission measured 4.8×10^3 pc cm^{-6} if $T_e = 7000$ K. Combining this with our density estimate of 100–150 cm^{-3} implies a thickness for the ionized material of 0.2–0.5 pc, or, for a diameter of 10 pc, $\Delta R/R \sim 0.02$–0.05. These figures correspond to an effective filling factor of the whole shell of 0.06–0.14.

The detailed emission line spectrum depends on three main parameters, the ionization temperature of the central star, T_{ion}, the metallicity, and the mean ionization parameter, $\langle Q \rangle$, defined as the ratio of the number of ionizing photons passing through a unit area, divided by the particle density. The ratio of the He II λ4646 line to Hβ is a sensitive indicator of excitation temperature, but is only weakly dependent on the ionization parameter. This is illustrated in Table 5. From the models, we cannot reproduce this ratio, even for optically thin models, except in the case that $T_{ion} > 1.5 \times 10^5$ K. If the nebula is optically thick, then Table 5 would imply $T_{ion} = 175{,}000$ ($\pm 25{,}000$) K.

TABLE 5

DEPENDENCE OF THE He II λ4646/Hβ RATIO AND THE THICKNESS OF THE IONIZED SHELL ON THE IONIZATION PARAMETER AND EFFECTIVE TEMPERATURE

	log ⟨Q⟩		
T_{eff}	8.0	7.5	7.0
100,000	0.121	...	...
150,000	0.408	0.417	0.345
200,000	0.684	...	...
$\Delta R/R$	0.276	0.059	0.022

We assume that the filling factor of the ionized plasma is unity in the compressed H II region shell, which is confined by the hot shocked stellar wind gas. In this case, the thickness of the ionized shell can be used to estimate $\langle Q \rangle$, since this thickness is so strongly dependent on the ionization parameter. In Table 5, the value of $\Delta R/R$ computed in a set of models where $R = 10$ pc is given. Comparison with the observational value given above implies log $\langle Q \rangle = 7.3(\pm 0.3)$ cm s^{-1}. The ionization parameter may also be estimated from the [S II]/Hα ratio. As is the case for H II regions (Evans and Dopita 1985; Dopita and Evans 1986), this ratio is strongly (positively) correlated with the ionization parameter $\langle Q \rangle$. In order to reproduce the observed ratio, the models indicate a value of log $\langle Q \rangle = 8.0(\pm 0.3)$ cm s^{-1}. This is probably the more reliable of the two estimates. The ionized mass of the nebula is therefore in the range 300–1000 $M_\odot$.

A detailed photoionization model which reproduces the observed line intensities turns out to be rather difficult to construct. Twenty-five models were run in order to determine the influence of the various parameters on the emergent spectrum. The major problem is to reproduce the observed [O III]/Hβ ratio. It is already known that, for H II regions with normal exciting stars, this ratio is strongly sensitive to the effective temperature of the exciting star and the chemical abundances, but is only weakly dependent on the ionization parameter at the higher temperatures (Evans and Dopita 1985; Dopita and Evans 1986). A similar result obtains when we go to the much higher ionization temperatures appropriate to G2.4+1.4. Indeed, the hotter the star, or the flatter the UV spectrum, the stronger is the [O III] line with respect to Hβ. At a constant ionization parameter, the same is true of the relative strengths of forbidden lines of other ions. Our models for simple black-body distributions all have [O III] λ5007/Hβ ratios ≥ 10, compared with the observed value of ~5. This is a serious discrepancy, since the [O III] lines are one of the principal coolants, and thus the [O III] λ5007/Hβ ratio is a fundamental diagnostic ratio. Making the nebula optically thin does not help to solve this problem, as the optically thin models are

TABLE 6

PHOTOIONIZATION MODELS FOR G2.4+1.4

Ion	Line Flux with Respect to Hβ = 100.0			
	Observed	Model A	Model B	Model C
[O II] λ3728	>55:	152	147	133
He II λ4686	55	40	55	43
Hβ λ4861	100	100	100	100
[O III] λ4959	157	245	352	240
[O III] λ5007	472	707	1010	690
He I λ5876	5:	11	17	17
[O I] λ6300	11:	9	8	7
[O I] λ6363	5:	3	3	2
[N II] λ6548	15	40	38	37
Hα λ6563	272	297	295	298
[N II] λ6584	42	118	112	109
He I λ6678	4	3	5	5
[S II] λ6717	19	20	19	19
[S II] λ6731	15	17	16	16
[Ar III] λ7165	23	10	10	10
[O II] λλ7318, 7330	4:	1	1	1

B. MODEL PARAMETERS

Parameters	Model A	Model B	Model C
T_{eff}	1.5×10^5	1.75×10^5	1.5×10^5
$\langle Q \rangle$	1.0×10^8	1.0×10^8	1.0×10^8
$n\,(\mathrm{cm}^{-3})$	150	125	125
R (pc)	5.0	5.5	5.5
$N(\mathrm{He})/N(\mathrm{H})$	0.1	0.15	0.14
$Z/Z_{\odot}$	4.0	4.0	4.0

more sensitive to the high-temperature plasma which exists in the inner regions, which has a higher intrinsic [O III] λ5007/Hβ ratio.

In order to obtain values of the [O III] λ5007/Hβ ratio which approach the observed value, the gas must have a sufficiently high metallicity to weaken the [O III] lines as a result of the decrease in electron temperature of the plasma. We find that, in order to give a reasonable fit with observation, an abundance of order 4 times solar is required. Finally, a model which gives an optimum fit with the observed ratio of [O III] λ5007/He II λ4686 requires a somewhat lower ionization temperature, coupled with a slight overabundance of He, ~0.13 by number. These numbers suggest that some mixing of the chemically enriched wind with the surrounding medium has occurred. The line intensities given by the models which most closely approach the observational results are summarized in Table 6.

Given the ionization parameter, stellar temperature, and the nebular density and radius, then the effective radius of the star can also be estimated. In Figure 6, we show the dependence of the effective radius of WR 102 on the ionization parameter for various ionization temperatures, assuming a nebular radius of 5.5 pc. The parameters which best define the central star

$$\log (T_{\mathrm{ion}}) = 5.20 \pm 0.05; \quad \log (R/R_{\odot}) = 0.05 \pm 0.20;$$

$$\log (L/L_{\odot}) = 5.85 \pm 0.20.$$

Maeder (1983) has shown that WR stars conform to a rather narrow mass/luminosity strip defined by

$$\log (L/L_{\odot}) = 3.8 + 1.5 \log (M/M_{\odot})$$

which implies that the current mass of WR 102 is of order 15–30 $M_{\odot}$. However, the initial mass is difficult to estimate from these parameters, since the evolutionary calculations of Maeder show that a wide mass range of stars may evolve to endpoints with similar parameters. All that can be said is that the initial mass almost certainly exceeded 60 $M_{\odot}$. The position of WR 102 on the Hertzsprung-Russell diagram is also consistent with a star on the C–O main sequence. Its extreme parameters place it firmly in the régime where the atmosphere is optically thick to electron scattering, which generally results in the effective temperature, T_{eff}, being much lower than the ionization temperature, T_{ion} (Abbott and Conti 1987).

V. CONCLUSIONS

We conclude that all the optically observed properties of the filamentary nebula G2.4+1.4 are consistent with the effects of violent mass loss from the extreme WO star, WR 102, near its center. This star is shown to be a stripped C–O core, without a trace of residual helium in the atmosphere. The analysis of the

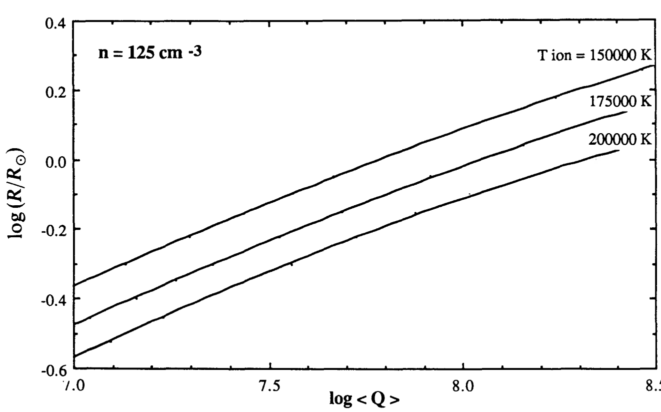

FIG. 6.—The relationship between ionization parameter and the effective radius of the central star, as derived from photoionization models.

nebular spectrum enables us to put strong constraints on the temperature, luminosity, and mass of WR 102. These firmly establish the star as a relatively distant, extreme Population I object, which had an initial mass of at least 60 $M_{\odot}$.

New observational data, and an analysis of the internal dynamics of this nebula, will be the subject of a later paper. However, these data are consistent with the picture presented here.

The radio spectrum presented by Johnson (1975) is the major problem with our model, since this suggests that the nebula is emitting as a nonthermal source. It is therefore important that an attempt be made to remeasure the radio spectrum in order to verify the nature of the radio emission.

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