G2.4+1.4: AN EXTRAORDINARY MASS-LOSS BUBBLE DRIVEN BY AN EXTREME WO STAR

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ABSTRACT. The nebula, G2.4+1.4, is shown to be a highly reddened, photoionised, mass-loss bubble of very high excitation powered by WR 102, the most extreme oxygen sequence Wolf-Rayet star known. It lies at a distance of 3±1kpc, and is about 11 pc in diameter. The exciting star, contains neither hydrogen nor helium in its atmosphere, is losing mass at a velocity of 5530 $km.s^{-1}$, and has the following properties: $\log (T_{ion}) = 5.20\pm0.05$; $\log (R/R_{\odot}) = 0.05\pm0.20$; $\log (L/L_{\odot}) = 5.85\pm0.20$. We conclude that the star is the $\sim20M_{\odot}$ core of a supermassive star ($M \leq 60M_{\odot}$) seen near the end of its life.

1. Introduction

The ultra-violet strong object discovered by Blanco *et. al.* (1968), known variously as WR 102, Sk 4 or LSS/LS 4368 is possibly the most extreme example of a Wolf-Rayet star of the Oxygen sequence known. An extrapolation of the line ratio and line width classification criteria would imply a classification of WC 4.

The nature of the surrounding radio source, the nebula G 2.4 +1.4, has been the subject of considerable debate over the years (Goss and Shaver 1968; Johnson, 1973, 1975; Treffers and Chu, 1982; Chu *et al.*, 1983; Green and Downes, 1987; Caswell and Haynes 1987), and the interpretation of the nebula as a supernova remnant, wind blown bubble around the WO star, or some compound model, have all been considered .

In this paper, which is an abbreviated account of papers published in the *Astrophysical Journal* (Dopita *et al.* 1990; Dopita and Lozinskaya, 1990), we present spectrophotometric and kinematic data on both the star and its surrounding nebula and show that the nebula is in fact a mass-loss bubble powered by the central star. We derive the parameters of the central star and energetic estimates for the nebula.

2. The Nature of WR 102.

The stellar classification given by Freeman *et al.* (1968): WC 4-5 pec, has subsequently been broady accepted (see, for example, van der Hucht *et al.* 1981 or Lundstrom and Stenholm, 1979). Sanduleak (1971) listed five WR stars which show very strong OVI -emission, two of them in the Magellanic Clouds. One of the Galactic examples, Sk 3, is the central star of a very old PN (Barlow and Hummer, 1982). According to current understanding the remaining Sanduleak stars should be considered as a separate Population I WO sequence, defined by the relative strengths of O IV, O V and O VI, representing an evolutionary stage following 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. On the basis of its excitation, Sk4 (WR 102) is the most extreme Population I WR star known.

In order to clarify the evolutionary status of WR 102, we obtained spectrophotometry in the range 0.34 - 0.82 μm and infrared spectra in the range 1.0 - 2.5 μm. These spectra are

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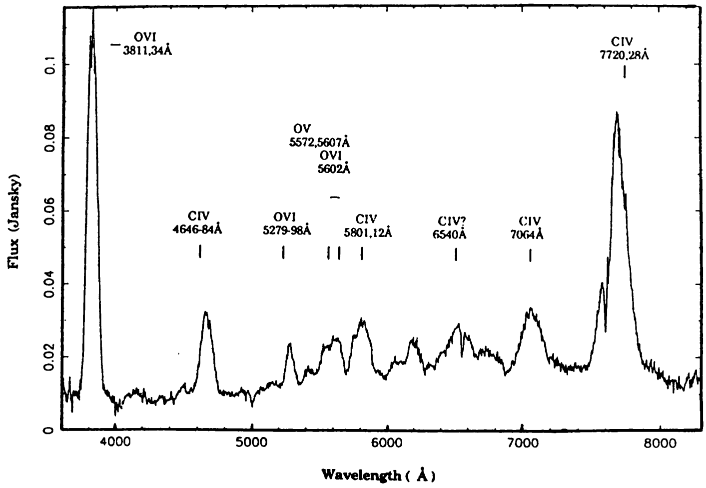

Figure 1. The optical spectrum of WR 102, showing OV, OVI, and CIV lines only.

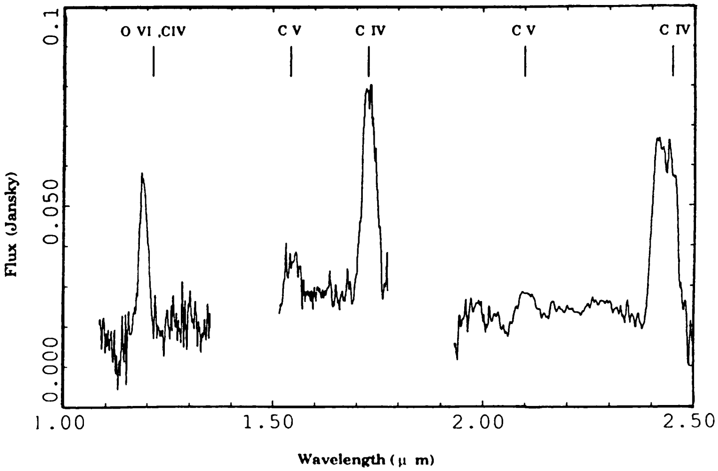

Figure 2. The IR spectrum of WR 102, dominated by CIV and C V emission lines.

shown in Fig 1 and 2. The strongest spectral features are due to resonance lines of O VI and C IV. The near-IR spectrum of WR 102, shown in Figure 2 is dominated by strong broad emission lines of C IV superimposed on a smooth continuum which is essentially flat in F_ν between 1.0 and 2.5μm. The continuum is probably due to optically-thick free-free emission (Barlow and Hummer 1982), and the principal emission lines are those of C IV (Williams 1982). Lines of C V (10-9) 1.55 μm and CIV (11-10) 2.11 μm may also be present.

There is no sign of either hydrogen or helium in this spectrum. In particular, the He I ($2s\ ^1S$ - $2p\ ^1P$) transition at 2.058 μm and the He I ($3p$ - $4s$) lines at 2.11 μm are completely absent in WR 102. Thus, we can exclude the possibility of He I lines in the spectrum. The possibility of He II emission is not excluded by the optical data, since the 0.466μm feature may be a blend of CIV with the He II line. However, the IR data show no sign of the He II features at 1.165μm, 1.27 - 1.29μm , 2.037μm , 2.164μm and at 2.31 -

2.37μm (Hillier, Jones and Hyland 1983).These data give the most uneqivocal 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 velocity inferred from the FWZM of the unblended or very closely separated lines yields $V_w = 5530(\pm 200)$ km.s^{-1}. (*c.f.* 5500 km.s^{-1} ; Barlow and Hummer 1982 and 5700 km.s^{-1} ; Torres et al. 1986). At this velocity, each solar mass lost carries 3.10^{50} ergs to the interstellar medium (ISM). Thus 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.

The distance to the star is quite difficult to estimate, given the small number of such stars against which it can be compared. The two examples of WO stars in the Magellanic Clouds are both of class WO4 (Barlow and Hummer, 1982). However, the LMC example is a binary, and cannot be used in a comparison of distances. The SMC star, Sand 1, has V = 14.44, (B-V) = 0.08, which implies an absolute magnitude $M_V \sim -2.4$. If WR 102 has the same absolute magnitude, then with V = 14.64, $A_V = 4.3$, a distance of 3.5 kpc is derived. Perhaps a better way to estimate the distance is to use the other Galactic example of a WO star, WR 142 (ST 3, Stephenson (1966); Sand 5), of spectral class of WO2, more like that of WR102 (WO1). It lies at a distance of 946±26pc and has <E(B-V)> = 1.7±0.1 (Turner and Forbes, 1982). A direct comparision of the observed magnitudes and reddening V = 13.56, $5.3 < A_V < 6.2$ with those of WR 102 (V = 14.64, $A_V \sim 4.3$) implies a distance in the range 2.5 - 3.6 kpc. On this basis we estimate of 3±1 kpc for the distance to G2.4+1.4.

3. OBSERVATIONS OF G 2.4 +1.4.

3.1. Hα IMAGING

Images of G2.4 +1.4 obtained by Johnson (1975) and Treffers and Chu (1982) show an inner highly symmetrical filamentary shell, 5 arc min. in diameter which is embedded in a larger shell-like structure extending about 8 arc min in the NE-SW direction. The exciting star WR 102 lies some distance from the center of either of these structures.

Following our discovery of extended faint emission, we performed deep Hα narrow-band imaging on the the red arm of the Double-Beam spectrograph (Rodgers *et al.* 1988a) of the

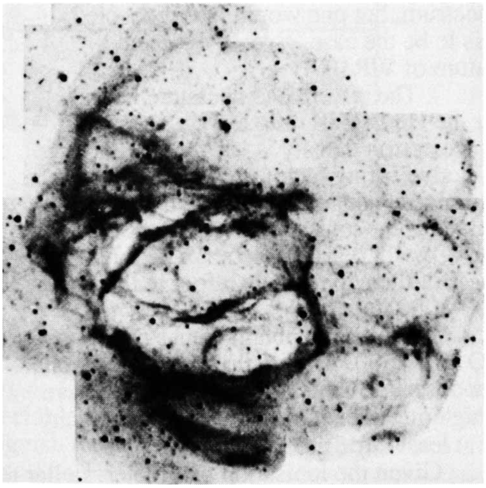

Figure 3. A deep H-Alpha composite image of G 2.4+1.4. North is at the top, and East to the left.The darkest filaments are those known previously.
Note the scalloped outer shell extending to the North and to the West which this image reveals for the first time.

2.3m telescope at Siding Spring Observatory. 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.* 1988b). The system acted as an f/1.5 camera with a scale at the focal plane of 1.0 arc sec.pixel^{-1}.

The image resulting from the combination of nine separate pointings is shown in Figure 3 on a logarithmic intensity scale, to bring out the fainter features. The nebula is revealed to be appreciably larger than hitherto supposed, with a complex double shell structure. The outer portions are scalloped in a semi-regular pattern about 3 arc min. in diameter, suggestive of a large-scale instability.

3.2. SPECTROPHOTOMETRY

We have obtained spectrophotometry of the nebula in the range 0.34-0.78μm using the double beam spectrograph of the 2.3m telescope. From four slit positions, the spectra of the ten brightest filaments were extracted, and the data from the brightest of these filaments were coadded to optimise the detection of faint lines. The resultant average spectrum is given in Table 1. The spectrum is like a PN of Excitation Class 7.5, as noted by Johnson (1976).

This spectrophotometry provides a strong constraint on the mode of excitation of the nebula. If shock excited, then models (e.g. Dopita et al. 1984) show that the [S II] and the [N II] lines would be comparable in strength with Hα. Furthermore, these 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 our observations, and with the narrow-band imaging observations of Treffers and Chu (1982). The observation of a strong [Ar III] line makes it almost inconceivable that the nebula is shock-excited, since this line is normally emitted in a high-temperature zone in shocks, and as a consequence, the line is always very weak compared with photoionised plasmas.

From these arguments we conclude that the nebula is a radiatively-excited wind-blown bubble. We have constructed isobaric steady-state photoionisation models using the general-purpose modelling code MAPPINGS (Binette, Dopita and Tuohy 1985).

The results of a typical model are given in Table 1 (opposite). The spectrum is not particularly well fitted by the assumption of a Black-Body ionising spectrum, but one would have expected this to be the case, given the extreme nature of WR102.

The effective temperature implied by the He II / Hβ ratio is $T_{ion} > 1.5.10^5$K. The electron density is ~150 cm^{-3}, and an effective filling factor of 0.06 - 0.14 is estimated. The models also indicate a value for the ionisation parameter of log<Q> = 8.0 (±0.3) cm.s^{-1}. The ionised mass of the nebula is therefore in the range 300-1000M$_{\odot}$.

In order to obtain values of the [O III] λ5007Å/H$_{\beta}$ ratio which approach the observed value, the gas must also have a high metallicity. We estimate a metallicity of at least three times solar.

Table 1: Photoionisation Model for G 2.4+1.4

λ (Å)	Ident.	Flux (Hβ = 100.0) Observed	Model
3728	[O II]	>55:	152
4686	He II	55	40
4861	H β	100	100
4959	[O III]	157	245
5007	[O III]	472	707
5876	He I	5:	11
6300	[O I]	11:	9
6563	H α	272	297
6584	[N II]	42	118
6678	He I	4	3
6717	[S II]	19	20
6731	[S II]	15	17
7165	[Ar III]	23	10
7318,30	[O II]	4:	1

Given the ionisation parameter, stellar temperature, and the nebular density and radius, then the effective radius of the star can be also be estimated.The parameters which we find to best define the central star are:

$\log (T_{ion.}) = 5.20\pm0.05$; $\log (R/R_\odot) = 0.05\pm0.20$; $\log (L/L_\odot) = 5.85\pm0.20$

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 WR102 has a mass of order 15 to $30M_\odot$. However, the initial mass is difficult to estimate from these parameters, since Maeder's evolutionary calculations show that a wide mass range of stars may evolve to endpoints with similar parameters. However the initial mass certainly exceeded $60M_\odot$, and the position of WR 102 on the H-R Diagram is 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 an effective temperature, T_{eff}, much lower than the ionisation temperatute, T_{ion} (Abbott and Conti, 1987).

3.3. INTERNAL DYNAMICS

We sampled the velocity profiles at some 55 points at a resolution of 8.8 km.s^{-1} using the échelle spectrograph at the Coudé focus of the 1.8m telescope at Mt. Stromlo. Across the whole nebula we find emission at or near $V_{HeI} = 13\pm5$ km.s^{-1} ($V_{LSR} = 23\pm5$ km.s^{-1}). This feature is broad, and is brighter than the [O III] profile from the nearby sky. Furthermore, the line profiles show substantial variation across the nebula, so this component is certainly a part of the nebula. This feature is narrowest in the diffuse region on the south side of the nebula. We also find a line component with high negative velocity, between -38 km.s^{-1} $\leq V_{HeI} \leq 5$ km.s^{-1} (-28 km.s^{-1} $\leq V_{LSR} \leq 15$ km.s^{-1}) (*c.f.* Johnson 1975,1976; Treffers and Chu 1982 a). Largest negative velocities are found in the vicinity of WR 102. This further strengthens the case that the central star WR 102 is both the exciting source for the nebula, and is also the source of the kinetic energy of G2.4+1.4.

A simple velocity ellipsoid will not work in the case of G2.4+1.4 because rapid motions characterise only one side of the shell, and because this shell is non-spherical, as seen in projection. We therefore adopted a simple model of a single hemispherical shell with different radii of curvatures in its northwest and its southeast portions, shown in Fig. 4.

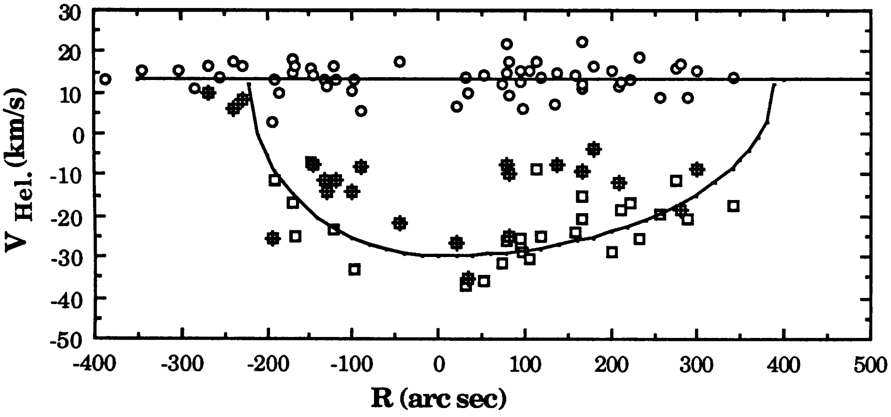

Figure 4. The velocity ellipsoid for G2.4+1.4. Circles are measured velocities on the farside of the shell which does not show appreciable expansion. The squares are for points on the nearside, and squares with crosses distinguish the brighter filaments. The line is a model of asymmetrical hemispherical expansion.

The velocity of expansion of the nearside of the shell is 42 km.s^{-1}, whereas the far side of the shell shows no systematic expansion. The brighter filaments are characterised by a systematically lower velocity of expansion, of order 20 - 30 km.s^{-1}, a result characteristic of bright filaments in energy-driven bubbles (as well as in old SNRs; Lozinskaya, 1980; Lozinskaya *et al.* 1988). This is what is expected if the bright filaments result from a cloudy shell which is swept up and accelerated by the wind.

For the case of a bubble evolving into a constant density medium, the relationship beween the radius of the bubble, *r*, its velocity of expansion ,V_{exp}, the density of the ambient medium, *n*, and the energy input rate, $\partial E/\partial t$ is given by;

$$r = 1.7(\partial E/\partial t_{36} / n)^{1/5} \, t_4{}^{3/5} \text{ pc.}$$
$$V_{exp} = 100 (\partial E/\partial t_{36} / n)^{1/5} \, t_4{}^{-2/5} \text{ km.s}^{-1}$$

However, in the case of G 2.4 +1.4, the uniform density assumption is clearly wrong. For an average filament density of 30 - 60 cm^{-3}, and a mean temperature of 8000 K, derived from the photoionisation analysis, we estimate that the pre-shock density on the low density side of the expanding bubble is 2 - 4 cm^{-3}, and on the dense side, about 30 - 60 cm^{-3}. In a medium with a strong density gradient, the shock moving into the denser medium is slowed, and stalls when its velocity drops below the sound speed in the pre-shock medium. Assuming that the bubble expanded in the dense medium to a radius of ~3 pc (about 200 arc sec. on the sky), before breaking out into the lower density medium, and applying the above equations, we estimate an age at breakout of (1.8±0.3)x10^5 years. A mechanical luminosity of $\log(L/L_\odot) = 2.0\pm1.3$ was sufficient to power the bubble. On the other hand, the central star delivers $\log(L/L_\odot) \sim 4.7\pm 0.4$; far greater than what is needed.

Chu (1982) and Treffers and Chu (1982*b*) derived the kinetic efficiency of a stellar wind bubble , ε, to be the ratio of the kinetic energy in the expanding bubble to the kinetic energy delivered by the central star over its mass losing lifetime. For five wind bubbles associated with W-R stars they found ε is about 0.01. Athough we have derived the ratio of the instantaneous production of mechanical energy to the mean energy production rate, it is clear that our efficiency parameter is also required to be about 0.01, or even less. Van Buren (1986) suggested a mechanism whereby the efficiency can be reduced in the case of evolution in a clumpy medium. Here the clumps inside the bubble are rapidly evaporated, lowering the internal temperateraturе of the bubble, and allowing cooling to become important. In this the expansion will become momentum-conserving.If this were the case, then we find an age of $\log(t / yr) = 5.1\pm 0.6$; in good agreement with our estimates of the dynamical age. We therefore conclude that the momentum conserving solution probably applies.

Finally, the characteristic scallops in the outer parts of the bubble to the west, are strongly suggestive of an instability with some characteristic scale length in the ionised shell. The most likely explanation is that here we are seeing a developed Rayleigh-Taylor (R-T) instability. This instability was probably produced at the time of shock breakout, in the layers with a strong density gradient, where continuing acceleration of the nebular shell will occur. This has clearly occurred in G 2.4 +1.4, as we see a dynamical distinction between the bright filaments and the more diffuse material. The bright filaments both lie within the outer shell, and are moving more slowly, both of which would result from the R-T instability in the compressed shell. We estimate the timescale for the development of a RT instability is of order $(\Delta R/g)^{1/2}$, where ΔR is the thickness of the filaments, approximately 5x10^{17} cm, and *g* is the effective gravity. From both the dynamical data, and the morphology of the nebula, we derive a current age of 2.7x10^5 years for the whole structure (9x10^4 years since breakout). In order to produce the observed scalloping, this requires an acceleration of ~10^{-6} cm.s^{-2} in the ionised layer, which in turn implies a growth time for the RT instability of order 2x10^4 years; comfortably shorter than the evolution time.

4. 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, WR102, near its centre. This star is shown to be a stripped C-O core of a Population I star with an initial mass of at least $60M_\odot$. We may also conclude that the surrounding nebula, G2.4+1.4, is a photoionised mass-loss bubble about 10^5 years old, driving into a medium with a strong intrinsic density gradient. This has encouraged the development of Rayleigh-Taylor instabilities which result in the characteristic morphology.

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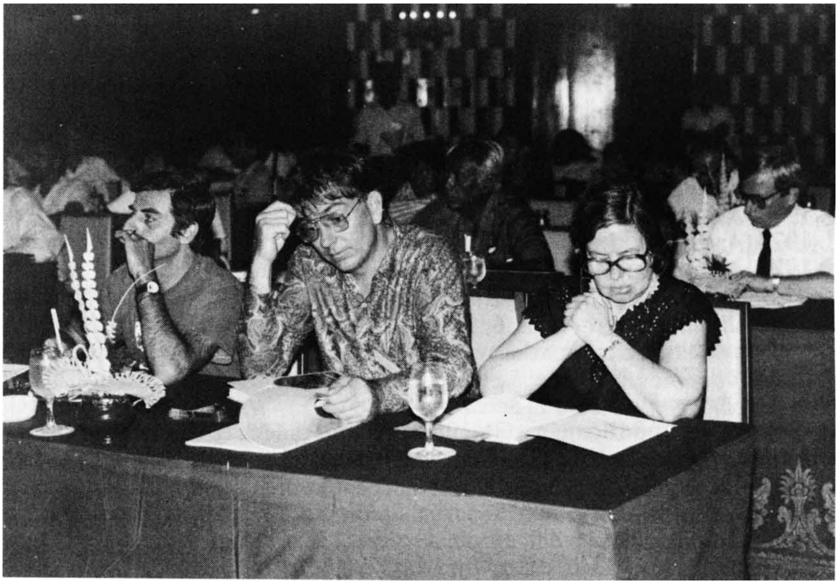
DISCUSSION

Niemela: Can you estimate the local standard of rest central velocity of the nebula?
Dopita: Yes, $v_{LSR} = +23 km \cdot s^{-1}$. Because of its position, almost towards the galactic centre, this is not very useful for getting an estimate of the distance.

Langer: If you conclude the central star is in a very late evolutionary stage, you should not apply the M-L relation for WR stars to derive its mass, since it is only valid for core He-burning stars. You would over-estimate the mass by that.
Dopita: Agreed, the star is on the "CO" main-sequence rather than the "He" sequence, and so the mass may be less than $20 M_{\odot}$, possibly as low as the 6-$10 M_{\odot}$ as you would like to have.

Vilchez: (1) How does your T_{eff} determination compare with other methods, *i.e.*, is it an "ionization temperature"? (2) How is the systematics of the multiple components in velocities over the nebula?
Dopita: (1) Yes it is an ionization temperature. It is higher than the "Zanstra" temperature (Heydari-Malayeri, this symposium). However, this problem is analogous to the Zanstra discrepancy in PN, and the ionization temperature is probably more reliable. (2) I think this is explained in the text of the paper.



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