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GALACTIC RING NEBULAE ASSOCIATED WITH WOLF-RAYET STARS. V. THE STELLAR WIND BLOWN BUBBLES

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ABSTRACT

Fabry-Perot observations at Hα and [O III] λ5007 are presented for the Wolf-Rayet ring nebulae NGC 2359, NGC 6888, and the nebulae around MR 100. The measured expansion velocity of these nebulae are 18, 75, and 50 km s^{-1}, respectively. The kinetic energy of the shells is 1% or less of the kinetic energy from the wind over the lifetime of the shell. This energy is more than a factor of 20 less than expected from the theory of stellar wind blown bubbles. The observed dynamics agrees better with the momentum conserving expansion than the adiabatic stage of wind driven expansion. The origin and role of density inhomogeneities are discussed.

Subject headings: interferometry — nebulae: general — stars: winds — stars: Wolf-Rayet

I. INTRODUCTION

Many Wolf-Rayet (W-R) stars are known to be associated with ring-shaped nebulosity. Johnson and Hogg (1965) proposed that some of these nebulae result from gas ejected from the star interacting with the surrounding interstellar medium. More generally, the interaction may involve one or more of the following: stellar UV radiation; ejected stellar material; or stellar winds. Chu (1981) has discussed the relative roles of these mechanisms for all known galactic Wolf-Rayet ring nebulae. We present below Fabry-Perot observations of three W-R ring nebulae in which the stellar wind may dominate.

II. OBSERVATIONS

All of the data presented here were obtained with a piezoelectrically-scanned Fabry-Perot spectrometer used on the 0.76 m telescope of the University of California at Berkeley. Details of the operation of this instrument can be found in Treffers (1981). The journal of observations is shown in Table 1.

Observations were made at Hα and [O III] λ 5007 and the velocities reduced to the local standard of rest (LSR). For Hα and [O III], respectively, the free spectral range is 213 and 161 km s^{-1}, and the instrumental profile has a FWHM of 15 and 20 km s^{-1}. Gaussian fits to the spectra are made using a least-squares fitting program which convolves the components with the instrumental profile. All line widths quoted below are therefore corrected for instrumental broadening.

The ordinate in the figures is the photomultiplier count rate in Hz. A source filling a 2′ diameter beam with a brightness at Hα of 1.0×10^{-6} ergs cm^{-2} s^{-1} sr^{-1} gives a peak counting rate of 12 Hz if the line width is 15 km s^{-1}. This calibration follows from an observation of the Hα line in NGC 7027 (Miller and Mathews 1972). The zero level in the spectra is arbitrary.

III. RESULTS FOR INDIVIDUAL OBJECTS

a) NGC 2359 (S298)

This nebula is a roughly spherical shell or bubble surrounded by a larger diffuse H II region. Since the central Wolf-Rayet star shows signs of mass loss, Johnson and Hogg (1965) concluded that the spherical ball was formed from interstellar material swept up by material ejected from the star such as a stellar wind, and that the diffuse nebula is ambient material photoionized by the star.

Several authors have studied the dynamics of this nebula; Lozinskaya (1973) and Pişmiş, Recillas-Cruz, and Hasse (1977) have obtained photographic Fabry-Perot spectra of this object, and Schneps (1979) has obtained photographic echelle spectra. All three authors conclude that the nebula is expanding but derive expansion velocities of 55 ± 25 km s^{-1}, ≈15 km s^{-1}, and between 15–30 km s^{-1} respectively. It was to sort out this uncertainty in the literature that we made new observations. Our data differ from previous observations in that they were obtained using a Fabry-Perot as a scanning monochromator in front of a photomultiplier tube. Two of the previous authors derived the velocity field from photographic images of the Fabry-Perot interference pattern. This latter technique presents a convolution of the velocity with the spatial distribution of material and may lead to errors when looking at spatially non-uniform sources.

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TABLE 1

JOURNAL OF OBSERVATIONS

Nebula	Line	Integration Time (s)	Date (UT)
NGC 2359 ...	Hα	7360	1981 Apr 4–5
	[O III]	4800	1980 Mar 6
NGC 6888 ...	Hα	9600	1980 Jul 15
MR 100	Hα	7440	1980 Oct 7
	[O III]	5120	1980 Oct 4

Figure 1 shows the Hα and [O III] spectra. Narrow band interference filter photographs of this nebula can be found in Schneps and Wright (1980). In order to remove the telluric Hα and OH lines in the Hα spectra, we subtracted a spectrum of a reference position 10′ north of the W-R star. The signal in this reference position is much less than that of the nebula.

It is clear from Figure 1 that the line width varies over the nebula, and that the velocity patterns in both Hα and [O III] are identical. At the edges of the shell, where the velocity is 52 ± 3 km s^{-1}, the FWHM of the line is about 32 km s^{-1} in Hα and 20 km s^{-1} in [O III]. These velocity widths are typical of those found in H II regions and results from the superposition of thermal motion with a turbulent velocity on the order of the sound speed (Dopita 1972). The line width increases towards the center of the nebula, implying that there is some nebular expansion. However, the expansion velocity is so low that two peaks are not apparent because of blurring by the line width of the plasma.

In order to estimate the expansion velocity, we have fitted the data in Figure 1 with two Gaussian components constraining their width to be the limiting values above. This technique was used by Bohuski and Smith (1974) to measure the expansion velocity of planetary nebulae. We derive a nebular expansion velocity of about 18 km s^{-1}. This agrees with the value derived by Pişmiş, Recillas-Cruz, and Hasse (1977) from the dispersion of the peak velocities of various filaments.

The nebula is embedded in a region that contains higher density than the normal ISM. The outer portions of this region are ionized by the star and can be seen very clearly in the [N II] photograph (Schneps and Wright 1980). Our Hα spectra (Fig. 1) of these outer regions show a single peak at a velocity of about 52 km s^{-1} and a FWHM of 20–25 km s^{-1}, which is a width consistent with photoionized hydrogen.

Schneps *et al.* (1981) have detected CO emission in the direction of NGC 2359 at velocities of 37, 54, and 67 km s^{-1}. The 54 km s^{-1} feature is concentrated to the south of the nebula and is certainly associated with the nebula. However, the association of the other two components is not so clear. There is no evidence for ionized material in our spectra with velocity of 37 or 67 km s^{-1}. We suggest that these other two CO features are foreand background features possibly associated with molecular clouds in spiral arms. Neutral hydrogen 21 cm spectra (Weaver and Williams 1973) in this direction show peaks at all three velocities which extend over many degrees.

b) NGC 6888 (S105)

The nebula NGC 6888 is a roughly elliptical nebula about $18'\times12'$ extent around the Wolf-Rayet star HD 192163. It is embedded in a much larger H II region S109. Many kinematic studies have been made of NGC 6888: Courtès (1960) detected motions on the order of 80 km s^{-1}; Georgelin and Monnet (1970) and Lozinskaya (1970) showed that there is a systematic expansion of between 50 and 110 km s^{-1}.

Figure 2 shows the Hα spectra of NGC 6888 on a grid of points centered on the star and separated by 2′. In order to remove the contribution from the extended nebulosity of S109, we have subtracted from all spectra a spectrum outside of the nebula. Since the background is not uniform, small errors can be seen in the weaker spectra to the west of the star.

The spectra are quite complex: in most locations, two components can be discerned, one brighter component at negative velocity and a second one at positive velocity which grows in intensity towards the southwest. In some locations, three components can be seen. This behavior can be best explained by an expanding shell in which the oncoming gas is brighter. From the two components near the center of the nebula, we derive an expansion velocity of 75 ± 5 km s^{-1} around a central velocity of 2.0 ± 5 km s^{-1}. The UV spectra of HD 192163 of Huber *et al.* (1979) show absorption lines of C IV and Si IV blueshifted by 90 ± 10 km s^{-1}. These lines are interpreted as arising from the high temperature interface between the hot stellar wind shocked gas and the swept up ISM.

In the [O III] photograph of Parker (1978), some filaments can be seen northwest of the W-R star which are outside of the bubble as defined in Hα. We have taken a spectrum of a position 2.′7 north and 8.′2 west of the central star with a 2′ beam in [O III] λ 5007. This spectrum shows a single peak at $V_{LSR}=6\pm5$ km s^{-1} with a FWHM of 40 km s^{-1}. It is not clear whether or not this filament is participating in the expansion since it is so near to the edge of the shell.

Johnson and Songsathaporn (1981) have presented a grid of [N II] profiles of the shell of NGC 6888 which also show the complex motions within the nebula. They argue that the nebula is composed of three wind driven cavities (Cantó and Rodríguez 1980). However, we disagree with their model. First, there is no evidence for neutral material associated with the shell; the H I data they quote are actually 21 cm continuum data. Second, the spectra in which the three components are most prominent are near enough to the edge of the nebula

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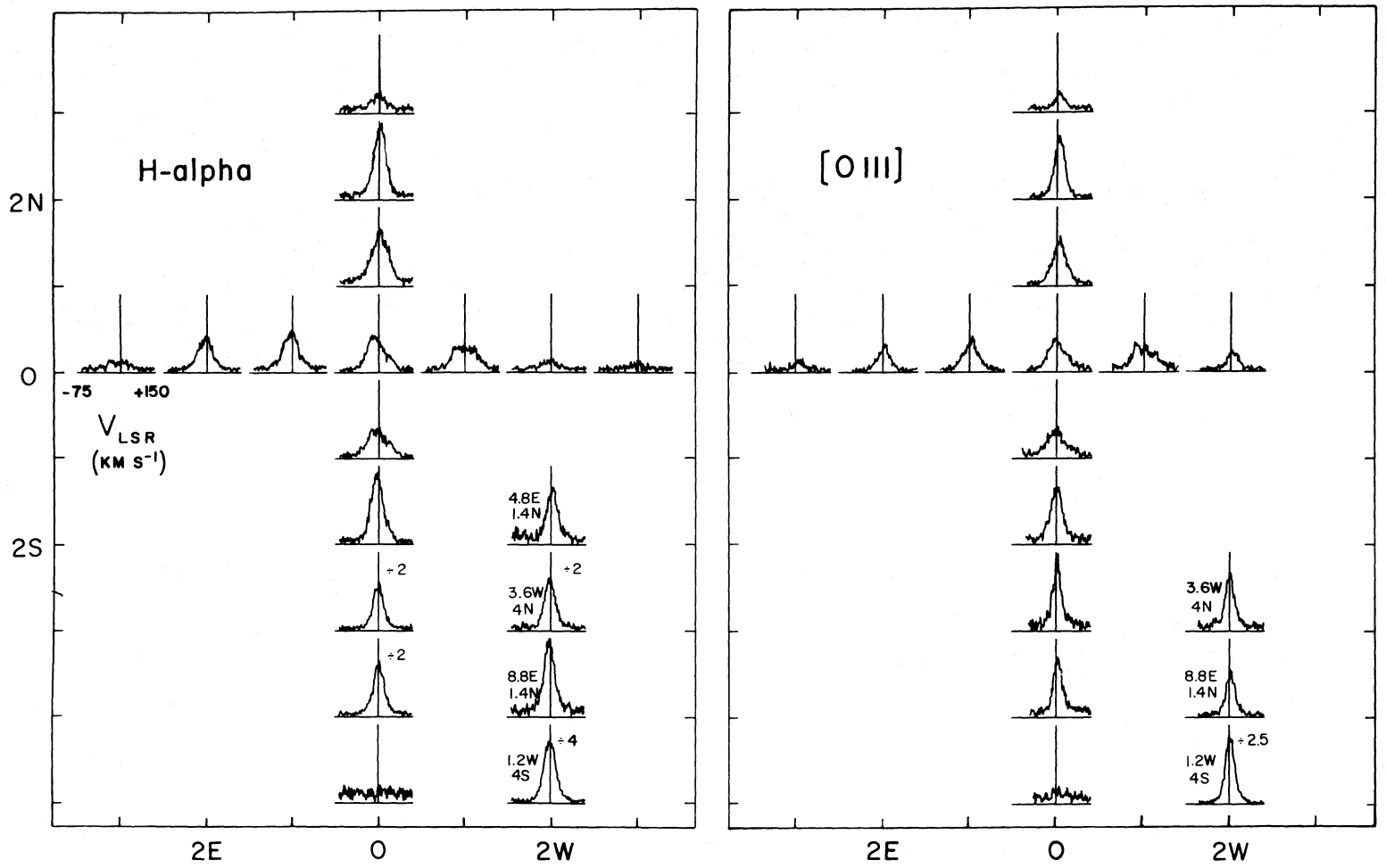


FIG. 1.—The Hα and [O III] spectra of NGC 2359. The unlabeled spectra are 1′ apart with the cross centered on the Wolf-Rayet star (HD 56925). The beam diameter is 1′. The spectra to the right are of the diffuse region outside of the spherical nebula and are offset from the W-R star by the listed displacements. The beam diameter for these spectra is 2′.

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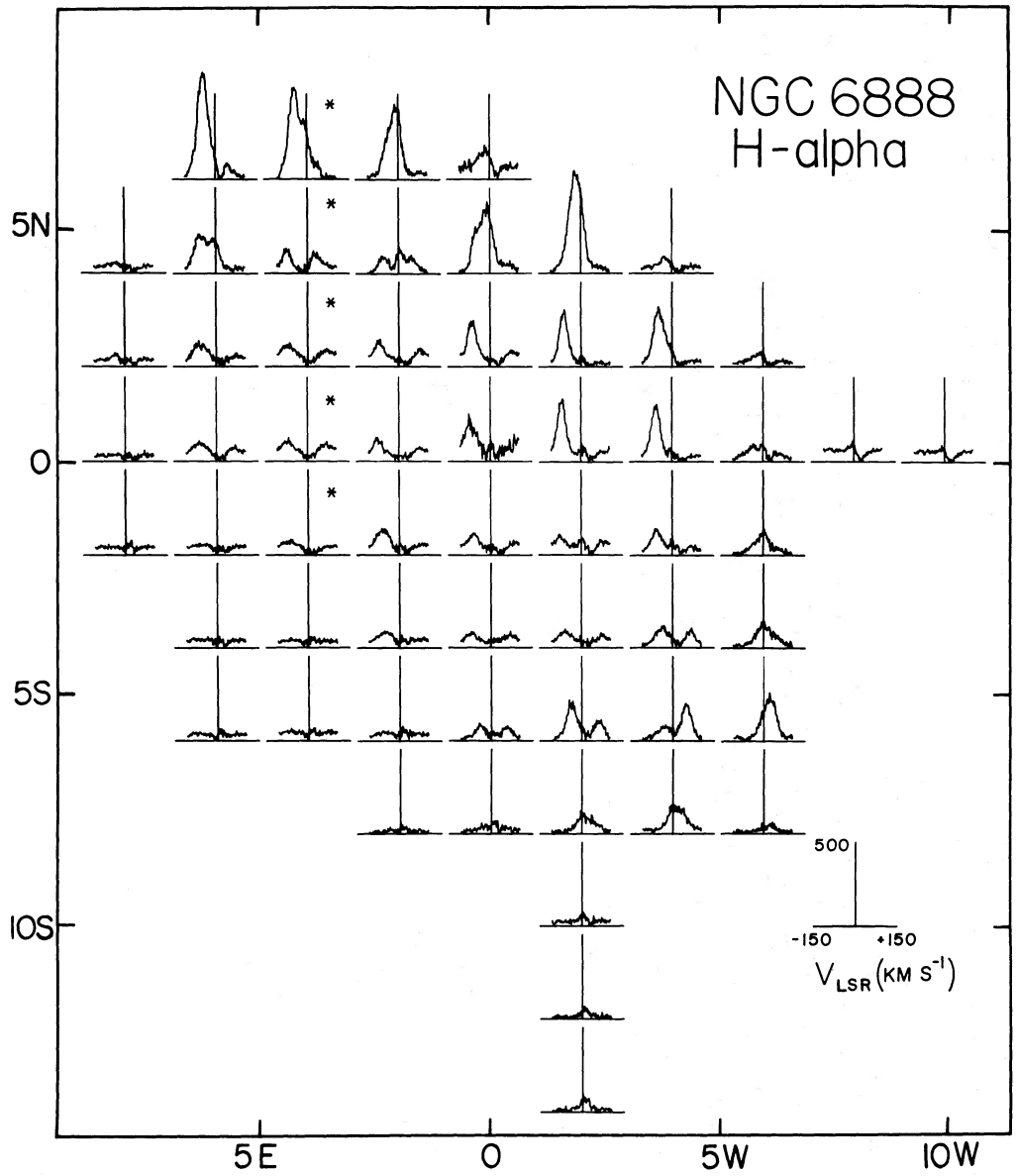


FIG. 2.—The Hα spectra of the nebula NGC 6888. The spectra were observed with a 2′ diameter beam on a grid with spacing of 2′. The position of the central W-R star is marked. The contribution from the background emission has been subtracted. Spectra marked with asterisks were also observed at low spectral resolution (§ III*b*).

that the change of radial velocity could be due to projection effects or could be density inhomogeneities trapped in the shell (§ IV*c*).

The observations of Lozinskaya (1970) and Wendker *et al.* (1975) discuss the possibility that there are diffuse and filamentary components to the Hα emission. Lozinskaya (1980) states that the FWHM of the Hα line in the diffuse component is 250 ± 50 km s^{-1}. We searched for this component using a free spectral range of 634 km s^{-1} at the locations of the spectra in Figure 1 marked with an asterisk. The spectra are not shown, since they show the same structure as the higher resolution data. There is no evidence for a broad component with an intensity greater than 0.05 that of the peak. One possible explanation of the difference between our spectra and those of Lozinskaya's is that we have subtracted the contribution from the emission of the superposed H II region (S109). Since this emission is concentrated near 0 km s^{-1}, it fills in the gap between the two peaks of the oncoming and receding shell and, in the fainter regions, gives the appearance of a single broad line.

c) Nebula near MR 100 (HD 191765)

This nebula does not have a name but was first noticed by Crampton (1971) in a survey of W-R ring

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nebulae. The nebula is also embedded in S109, the same large complex region which contains NGC 6888. Unfortunately, it is much fainter than NGC 6888 and is difficult to see clearly. In a photographic atlas of W-R ring nebulae (Chu, Treffers, and Kwitter 1982), the Hα photograph shows a single arc of nebulosity about 15′ southwest of the star. In contrast, their [O III] plate shows a filamentary structure to the northwest of the star. The filamentary morphology curving around the central star is similar to the other nebulae in which the stellar wind plays an important role (Chu 1981).

We obtained many Hα and [O III] spectra (Fig. 3) in order to separate the motion of the nebula from the motion of the background nebulosity. The nebula is much fainter in [O III], and therefore these spectra are noisier and have less complete coverage. The spectra are very complex; however, two components associated with the nebulosity can be discerned: one near 0 km s^{-1} and a second feature at 50 km s^{-1}. This latter feature can be seen blended in the Hα spectra and is brightest about 10′ west of the star. It is only seen in the region where the [O III] filaments are prominent. The 21 cm H I profiles in this direction (Weaver and Williams 1973) show that positive velocities greater than about 10 km s^{-1} are not expected in normal galactic rotation. We therefore conclude that the 50 km s^{-1} component is the receding portion of a shell around the W-R star. At a distance of 2.08 kpc (Barlow, Smith, and Williams 1981), the radius of the shell is 7.3 pc and its age (see § IV*a* below) is 9×10^4 yr. If the ambient hydrogen number density is 1 cm^{-3}, then the mass swept up into a hemisphere is 6.4 $M_\odot$.

IV. DISCUSSION

a) *Comparison with Bubble Theory*

We would like to investigate the hypothesis that the nebulae discussed above (with the exception of MR 100 since the data are much poorer) are driven by the stellar wind from the central Wolf-Rayet star. In this discussion we will include the W-R ring nebula S308 (Johnson and Hogg 1965; Chu *et al.* 1982) since it is very similar to those discussed here. We define two parameters, ε_s which is the ratio of the observed kinetic energy of the shell to the total kinetic energy emitted by the wind since the formation of the shell, and π_s which is the ratio of the current sheli momentum to the total injected wind momentum:

$$\varepsilon_s = \frac{M_s V_s^2}{\dot{M}_w V_w^2 t} \tag{1}$$

$$\pi_s = \frac{M_s V_s}{\dot{M}_w V_w t}. \tag{2}$$

These parameters represent the conversion efficiency of the stellar wind energy and momentum into motions in the interstellar medium. We will compare the observed values of these parameters with theoretical calculations of the evolution of wind driven shells.

We derive the shell mass (M_s) from the integrated radio flux and an estimate of the shell density from spectroscopic observations (Wendker *et al.* 1975; Schneps *et al.* 1981; Chu *et al.* 1981). Recent infrared and radio observations of Wolf-Rayet stars have given us good estimates of the mass loss rates ($\dot{M}_w$) of these stars (Barlow, Smith, and Willis 1981). For NGC 2359 we use the mass loss rate typical of other WN5 stars in Barlow, Smith, and Willis (1981). The wind velocities (V_w) are derived from *IUE* observations of the widths of resonance absorption lines (Barlow, Smith, and Willis 1981; Johnson 1980). The age of the shell (t) follows from observations of the expansion velocity, the radius of the nebula, and the manner in which the shell has decelerated. If the nebular radius (R) is proportional to the age of the shell to the power η, then

$$t = \eta \frac{R}{V_s}. \tag{3}$$

Different models give different values of η: a constant velocity of expansion gives $\eta = 1$, the wind energy conserving case (Avedisova 1972; Castor, McCray, and Weaver 1975) gives $\eta \approx 3/5$, and the wind momentum conserving case gives $\eta \approx 1/2$ (Steigman, Strittmatter, and Williams 1975).

The values of ε_s and π_s computed for the three nebula are shown in Table 2. It can be seen that ε_s lies in the range 0.0003–0.01. We can only estimate the uncertainty in these quantities. The mass loss rate and the mass of the shell are known to about a factor of 2. The wind terminal velocity, the expansion velocity, and the nebular age are known to about ±20%. If all these uncertainties combine in the same direction, an uncertainty in ε_s and π_s of a factor of 10 results. However, the uncertainty should be much smaller, since the errors are likely to combine in a more statistical manner.

There are additional sources of error in these parameters: it is possible that there is some material in the shell which is too cool to emit detectable optical or radio emission. Mass could be hidden in cool material if the ionization front is trapped within the shell. The presence of diffuse nebulosity in NGC 2359 shows that this is not the case; also, it is not expected to occur in NGC 6888 or S308 since their W-R stars have sufficient UV photons to ionize the present shells. Furthermore, we cannot exclude the possibility that the stellar wind was weaker in the past. However, the lifetime of the W-R phase is though to be a few times 10^5 yr (Chiosi, Nasi, and Sreenivasan 1978), and the mass loss rates of most of the W-R stars are roughly comparable (Barlow, Smith, and Willis 1981). Since these shells are relatively young, we

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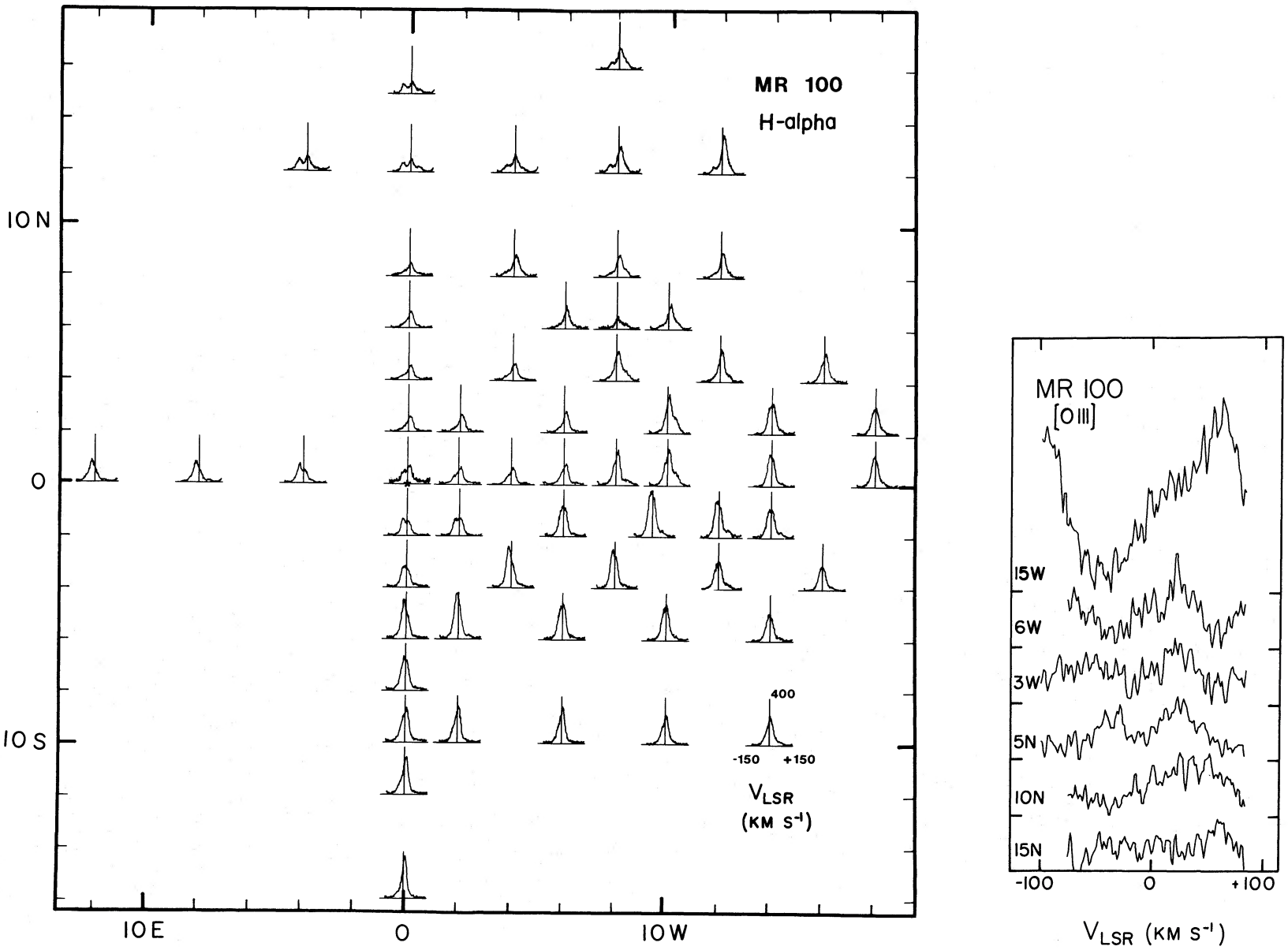


FIG. 3.—The Hα and [O III] spectra of the nebulosity around the W-R star MR 100. The position of the central star is shown.

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TABLE 2

SHELL AND WIND PARAMETERS

Parameter	NGC 6888	NGC 2359	S308	Units
Age	2.4	13	7.0	10^4 yr
Mass	5.0	16	40	$M_\odot$
V_s	75	18	60	km s^{-1}
$\dot{M}_w$	23	25	26	$10^{-6}\ M_\odot$ yr^{-1}
V_w	2250	2500	2700	km s^{-1}
ϵ_s	0.01	0.0003	0.01	...
π_s	0.3	0.04	0.5	...

do not believe that variability of the wind is a large source of error.

The interaction of a stellar wind with the surrounding ISM is a complex problem. Pikelner and Shcheglov (1969), Avedisova (1972), Dyson and deVries (1972), Falle (1975), and Castor, McCray, and Weaver (1975) have studied this problem for the case of a uniform distribution of ambient matter. In these calculations, the stellar wind passes through a shock wave and is heated to $T > 10^6$ K, and it is the pressure of this hot gas that drives the shock wave that sweeps up the ISM into a thin shell. In these calculations, on the order of 60% of the stellar wind energy goes into the internal energy of the gas, 20% into the kinetic energy of the shell, and 20% will have been radiated by the outer isothermal shock wave (Weaver *et al.* 1977). If the W-R nebulae are simple examples of this model, then our parameter ϵ_s should equal 0.2, which is greater than the observed value.

We believe that the low value of the conversion efficiency ϵ_s results from a loss of energy from the stellar wind by an undetermined mechanism. When this occurs, the radius at which the hypersonic stellar wind is thermalized increases (Weaver *et al.* 1977), the expansion law approximates that found in the momentum conserving case (Johnson and Hogg 1965; Steigman, Strittmatter, and Williams 1975), and the parameter π_s is of order unity. Indeed, the observations are in better agreement with the momentum conserving case for S308 and NGC 6888 than with bubble theory. For NGC 2359, the expansion velocity is so low that the Mach number relative to the outside ionized medium approaches unity, and therefore Alfvén waves can be emitted slowing down the shell even further. Momentum is then transferred to the external medium and is not accounted for in these observations.

We would like to find out how the stellar wind energy is lost and into what form it is degraded. We do not believe that it is radiated by the high temperature plasma inside the bubble. Although the cooling rate of the high temperature gas will be greater for the W-R ring nebulae that calculated by Weaver *et al.* (1977) because their winds are richer in metals, the nebula is at such an early stage of evolution that the radiation from the interior plasma should be small. The presence of the strong UV field from the W-R star makes it difficult to see whether the wind energy is dissipated in the shell. There are more than sufficient UV photons from the star (Morton 1973; Barlow, Smith, and Willis 1981) to excite the optical H II region.

Density inhomogeneities are the most reasonable possibility to account for the loss of stellar wind energy. Low density regions at the periphery of the shell will act as a "leak" for the high pressure gas inside nebula thus slowing down the expansion. Falle (1975) mentions that even small (20%) density inhomogeneities will allow the denser regions to cool faster and cause jets of hot material to flow around them. If clouds of material are embedded within the hot plasma they can radiate away the energy. These clouds will be slowly evaporated (Cowie and McKee 1977) and accelerated (McKee, Cowie, and Ostriker 1978).

b) The Origin of the Shell

The chemical composition of the stellar wind is expected to be similar to that in a WN star envelope (Willis and Wilson 1978) and therefore markedly difference from that of the normal ISM. In order for it to affect the abundances in the H II region, the hot plasma must enter the shell and cool. By observing the composition of the H II region, we can see whether the stellar material has mixed with the surrounding ISM.

Analyses of the elemental abundances in NGC 6888 and S308 have been presented by Kwitter (1979, 1981) and for NGC 2359 by Peimbert, Torres-Peimbert, and Rayo (1978) and Talent and Dufour (1979). Parker (1978) has studied the variation of [N II] and [O III] as a function of position in the nebula. All the authors agree that these nebulae show nitrogen and possibly helium enhancements over the normal ISM. Kwitter (1981) has shown that the composition of NGC 6888 can be explained quantitatively by mixing the stellar wind material ejected by the star over the lifetime of the nebula with the interstellar medium. In NGC 2359, the data are more uncertain, although it too is consistent with stellar wind enhancement of the nitrogen (Talent and Dufour 1979; Kwitter 1979).

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It appears that the stellar wind has been thoroughly mixed with the ISM, thus contradicting the simplest interpretation of wind energy conserving bubble theory. In the model of Weaver *et al.* (1977), the stellar wind material is thermalized by a collisionless shock into a high temperature plasma. Since the temperature of this plasma is so high the material will cool very slowly and is not expected to be at a temperature characteristic of an H II region. In their model, the interstellar material is mixed into the high temperature plasma and not the other way around as observed.

This picture is complicated by the fact that some W-R stars have ejected material, M1-67 (S80) is an example (Chu and Treffers 1981). This material is also rich in heavy elements and cannot be distinguished from the stellar wind material. It is possible that the enrichment of the nebulae discussed above is due to matter ejected by the star in the past, which has been swept up by the wind.

c) Nebular Asymmetry and Small Scale Density Structure

The optical photographs show that the shell of NGC 6888 is not spherical. Instead, the projected shape appears to be elliptical, with the northern side much brighter. The elliptical shape cannot be due to magnetic fields since they are too weak in the ISM to affect the dynamics (Avedisova 1972; Falle 1975). Asymmetry in the stellar wind cannot generate an asymmetrical nebula if bubble theory is correct, since the high pressure region is nearly isobaric (Falle 1975; Weaver *et al.* 1977). If the nebula were formed primarily from material ejected by the star, then it is possible that asymmetrical ejection could generate the observed shape. However, the discussion in § IV*b* and the large nebular mass involved argue against that interpretation. We therefore conclude that the shape of the nebula is a result of the nonuniform distribution of interstellar material.

This conclusion, however, presents a few problems. If the receding lines in NGC 6888 are formed in a less dense medium, they should be moving faster. This effect is not observed. Secondly, very large density differences must be responsible for the observed distribution because the higher velocity isothermal shock will compress the ambient medium more and thus compensate for the lower column density. One possibility is that the back side of NGC 6888 is connected to a very low density, high temperature tunnel in the ISM (Cox and Smith 1974). In this case, not enough material would have been swept up so that cooling would be significant (McKee and Hollenbach 1980). This would also vent the high pressure gas inside the bubble as discussed in § IV*a*.

Small scale density structures can be seen in all the expanding W-R ring nebulae (Chu 1981). Three possible mechanisms which could generate them are: (1) material which has been ejected from the star in some peculiar manner (Pişmiş, Recillas-Cruz, and Hasse 1977); (2) they are density inhomogeneities existing in the surrounding ISM which have been swept up and preserved on the surface of the bubble; (3) they result from instabilities in the shell. More detailed theoretical and observational work is needed to sort out these choices. One particularly puzzling result concerns the high velocity motions associated with the northwest filament in NGC 2359 (Pişmiş, Recillas-Cruz, and Hasse 1977; Schneps 1979). It can be seen in Figure 1 that the spectrum 1′ west of the star is anomalously broad. It is possible that these motions may result from the shock wave in the shell eating into clumps of enhanced density, although the high velocity is difficult to explain in the light of the low overall expansion velocity. These filaments may have instead been ejected from the central star (Pişmiş, Recillas-Cruz, and Hasse 1977).

V. CONCLUSION

All the evidence suggests that the W-R ring nebulae are formed by the interaction of the stellar wind from the W-R star acting on the interstellar medium. However, the observed energy of motion of the shell is far too small to be in agreement with the models of energy conserving stellar wind bubbles. It appears that there is some mechanism which dissipates the wind energy or prevents it from coupling with the mass motions. The composition of the nebula also points out a conflict with these models. The enhancement of metals suggests that the wind is well mixed with the ISM. This might be expected in the momentum conserving case in which the stellar wind impacts directly onto the shell of swept up interstellar medium.

Possible courses of investigation are the role of density inhomogeneities in the formation of stellar wind bubbles and the nature of the thermalization of the stellar wind. Detailed observations of the abundances and motions of individual filaments will also be required.

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