WINDS FROM HOT STARS

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ABSTRACT The winds of hot stars are significant sources of energy and momentum, as well as of nuclear-processed matter, for the interstellar medium. This paper reviews the relevant properties of hot stars and their winds and discusses our current understanding of both the large-scale effects of these winds on the galaxy, and the local effects on the evolution of H II regions and supernova remnants.

INTRODUCTION

In this paper I review the role of stellar winds in the deposition of energy and matter in the interstellar medium. I will consider only the winds of the hottest stars (spectral types O and B, and the Wolf-Rayet stars). Winds from pre-main sequence stars and from cool evolved stars are covered in reviews by Rodriguez and Knapp elsewhere in this volume.

The importance of stellar winds from the hottest stars has been fully appreciated only in the last decade or so. Two instruments have been essential to the development of our knowledge of these winds: the International Ultraviolet Explorer (IUE) and the Very Large Array (VLA). The IUE has made possible systematic studies of the spectra of a large number of OB and Wolf-Rayet (WR) stars. The UV spectra of these stars typically show P Cygni line profiles indicative of mass loss. Model analyses of the spectra have been used to determine mass loss rates and wind velocities. The VLA has provided complementary data on mass loss, especially for the most luminous hot stars, by detecting the (generally very weak) free-free emission from the ionized stellar wind. The VLA has sufficient sensitivity and angular resolution to measure the flux density of stellar wind thermal emission unambiguously (i.e., free of source confusion problems which limit even the largest single-dish radio telescopes), for a relatively large sample of stars.

Hot-star winds are astrophysically important for at least two reasons. First, they are a significant source of energy and of nuclear-processed matter to the interstellar medium. This aspect of these winds is the subject of this review. Second, the prodigious mass loss rates developed in these winds may have a profound effect on the evolution of the star. Evolutionary effects will not be discussed here; the reader is referred to the review by Chiosi and Maeder (1986) for an overview of the effects of mass loss on stellar evolution of OB and WR stars.

This review is divided into three parts: (1) the parameters of stellar winds for hot stars; (2) the calculation of global input rates of matter and energy into the ISM; and (3) local effects of stellar winds on both photoionized nebulae (H II regions) and on the development of supernova remnants.

STELLAR WIND PARAMETERS OF HOT STARS

In this section I review the relevant properties of mass-losing hot stars, including the types of stars which lose mass, mass loss rates, wind velocities, and correlations with other stellar properties.

Stars Which Lose Mass

The domain of mass loss in the HR diagram has been discussed by Abbott (1982a), who demonstrates that all stars with initial masses greater than 15 $M_\odot$ show evidence for mass loss in their visible and UV spectra. This criterion implies that all O-stars and all B0 dwarfs are expected to have winds throughout their lifetimes. (In this paper the terms "mass loss" and "stellar wind" are used more or less interchangeably, since the mass loss process occurs through a wind driven by the star. Because the wind velocity is greater than the stellar escape velocity–see below–the wind material is indeed lost from the stellar system.) Spectroscopic evidence also implies that virtually all B and A supergiants are also losing mass through winds. Finally, all Wolf-Rayet stars appear to have strong winds. In fact, the existence of a dense, massive wind may be a necessary condition for producing the characteristic emission line spectra which are a defining property of the WR stellar category.

Mass Loss Rates

Two approaches have been used extensively for determining mass loss rates from hot stars. The first method uses the continuum intensity of the free-free emission from the wind, together with the distance and wind velocity, to derive the mass loss rate, $\dot{M}$ (cf. Wright and Barlow 1975; Panagia and Felli 1975). The continuum intensity is best measured at microwave frequencies with the VLA, although in principle the IR excess (over the stellar photosphere) due to the wind can also be used. In this case, since the IR free-free emission is produced mainly from a region close to the star, the wind velocity as a function of distance from the star must be estimated or assumed to derive $\dot{M}$ (cf. Castor and Simon 1983). In contrast, at microwave frequencies, the thermal wind emission arises several hundred stellar radii from the star, where the wind can be assumed to have reached its terminal velocity. Moreover, the photospheric contribution at microwave frequencies is completely negligible, in contrast to the IR emission, where a photospheric contribution must be estimated and subtracted from the observed emission to obtain the wind contribution. For these reasons the mass loss rates derived from microwave flux density measurements are less model-dependent and therefore more reliable, than those derived from IR observations.

Mass loss rates derived from radio observations of a complete sample of OB stars have been published by Bieging, Abbott, and Churchwell (1989–see also references therein). Individual objects of particular interest have been studied by White and Becker (1982, 1983) and Becker and White (1985) and by Persi *et al.* (1985), who derive mass loss rates and other wind properties (e.g., wind temperature) from radio observations. Radio-derived mass loss rates of WR stars have been obtained by a number of workers (Seaquist 1976; Florkowski and Gottesman 1977; Dickel, Habing, and Isaacman 1980; Hogg 1982, 1985; Felli and Panagia 1982; and Bieging, Abbott, and Churchwell 1982). A complete sample of WR stars within 3 kpc of the sun and north of declination -47° was surveyed with the VLA by Abbott *et al.* (1986).

A complicating factor in the use of radio flux densities to determine mass loss rates of hot stars has become apparent over the past several years. Roughly one-quarter of all OB and WR stars observed show evidence–either in the radio spectral index, angular size, or time variability–for nonthermal radio emission, possibly from relativistic electrons accelerated by shock processes in the stellar wind. The distinction between thermal and nonthermal emission is essential to derive accurate mass loss rates and requires more than a single observation at a single frequency. For a more complete discussion, see Abbott *et al.* (1986) and Bieging, Abbott, and Churchwell (1989).

A second method which has been extensively employed to derive mass loss rates for OB stars is the analysis of UV spectra of C IV and N V, principally from IUE observations (e.g., Garmany *et al.* 1981; Garmany and Conti 1984). This method is most reliable for stars with low mass loss rates, since for high rates the UV lines become saturated. In this sense the radio continuum and UV spectral analyses are complementary. Abbott (1985) has shown that mass loss rates derived by these methods form a continuous sequence when plotted against bolometric luminosity, for values of L from 10^5 $L_\odot$ to 3×10^6 $L_\odot$. Garmany and Conti (1984) found, from a combination of UV and radio-derived values, that mass loss rates scale as a power of the stellar luminosity, with a best-fit relation

$$\dot{M} = 1.35 \times 10^{-7} (L/10^5\ L_\odot)^{1.62}\ M_\odot\ yr^{-1}$$

The scatter of the data around this fit is about a factor of 3 either way in $\dot{M}$.

This dependence of $\dot{M}$ on L is consistent with the predictions of radiation-driven wind theory, as formulated by Castor, Abbott, and Klein (1975) and subsequently refined (Abbott 1982b; Friend and Abbott 1986; Pauldrach, Puls, and Kudritsky 1986; Puls 1987). Attempts to parametrize the mass loss rate in terms of other stellar parameters–i.e., a "Reimers"- type law involving mass, radius, or effective temperature–give no obviously better fit. Van Buren (1985) finds no correlation between $\dot{M}$ and T_{eff}. The power-law correlation between $\dot{M}$ and L is generally regarded as convincing evidence that the winds of OB stars are driven by radiation pressure acting on absorption lines of the ions in the stellar atmosphere. However, the factor of 3 scatter in mass loss rates about the best-fit power law is not understood, but is probably larger than expected solely from observational uncertainties in the radio flux density, distance, and wind velocity.

Cassinelli and van der Hucht (1986) have reexamined the case for radiation-driven winds from WR stars. Based on revised surface abundances (but meager statistics) they derive mass loss rates which scale as $L^{2.0}$, or slightly steeper than for OB stars. There is however a serious "momentum problem" for the WR winds. The ratio of wind momentum, $\dot{M}V_\infty$, to radiative momentum, L/c, is much greater than unity for all WR stars with measured $\dot{M}$. This momentum excess is too large to be explained by the radiation-driven wind model, even with multiple scattering of photons. An (unknown) alternative mechanism may be the driving source of the WR winds.

Distances for OB stars are most reliably determined through membership in associations. For stars not in associations, the distance uncertainty, which enters as the 1.5 power in the calculation of $\dot{M}$, is typically worse than for cluster members. The WR stars in general have rather poorly known distances, which are generally the largest source of uncertainty in deriving $\dot{M}$.

Stellar Wind Velocities

The maximum velocity, V_∞, attained by the stellar wind must be known or estimated to determine both the mass loss rate, as discussed above, and to calculate the kinetic energy and momentum flux carried by the wind. V_∞ is generally determined in practice in one of two ways. For OB stars, the blue-shifted absorption edge of UV P Cygni lines which are optically thick throughout the zone of acceleration, gives V_∞ directly with typical uncertainties of about 10%. For WR stars, the reddening is often too large to permit good UV spectra. In such cases the width of optically thick emission lines can be used to obtain V_∞, with uncertainties typically 10 - 20%, depending on the star (see Abbott *et al.* 1986 for a more complete discussion).

For OB stars, there is a rather well-defined relationship between V_∞ and V_{esc}, the escape velocity from the stellar surface. Abbott (1982) found that

$$V_\infty = aV_{esc}$$

where

$$V_{esc} = (2GM(1-\Gamma)/R_\star)^{1/2}$$

is the escape velocity and $\Gamma = \sigma_e L_\star/4\pi GMc$ corrects the surface gravity for the effect of radiation pressure. The factor a depends on the stellar effective temperature, and varies between 1 for cooler stars (e.g., B0) and 3.5 for the hottest stars. This relation yields V_∞ to an accuracy of about 20% for OB stars. Van Buren (1985) found an alternative relation between V_∞ and T_{eff} only, with a rather larger dispersion of about 50% in V_∞.

For WR stars, there is considerable variation in values of V_∞ for stars of the same spectral type, as noted by Abbott *et al.* (1986). Thus estimates of V_∞ for individual WR stars may have errors of order 25% if based solely on average values by spectral type.

Wind Energies of OB and WR Stars

For OB stars, measured mass loss rates range up to $\sim 1 \times 10^{-5}$ $M_\odot$ yr^{-1}. These rates are expected to occur over the main sequence lifetime of a few million years, so the effect on stellar evolution can be profound (cf. Chiosi and Maeder 1986) for stars of spectral type O3 to O6. Since the mass loss rate scales approximately as $L^{1.6}$, the evolutionary effect is less severe for late O and B stars.

Measured wind velocities, V_∞, for O-stars lie generally in the range 1500 - 3000 km s^{-1}. The total kinetic energy carried by the wind can be estimated as the wind power, $(\dot{M}V_\infty^2)/2$, times the main sequence lifetime. For the most massive OB stars, the total kinetic energy carried by the wind is $\leq 10^{51}$ erg. Thus an early-O star may generate as much kinetic energy in its wind as that in a supernova remnant.

The wind velocities of WR stars are measured to be typically in the range 1500 - 4000 km s^{-1}. Abbott *et al.* (1986) found that mass loss rates of their sample of 40 WR stars within 3 kpc of the sun all lay within the relatively narrow range of 0.8 - 8.0 $\times 10^{-5}$ $M_\odot$ yr^{-1}, with an average value of 2 $\times 10^{-5}$ $M_\odot$ yr^{-1}. Van der Hucht, Cassinelli, and Williams (1986), using revised values of T_{eff} and atmospheric abundances, found mass loss rates which are systematically a factor of 2 to 3 higher than those of Abbott *et al.* (1986), i.e., $\dot{M} \sim 3$ to 10 $\times 10^{-5}$ $M_\odot$ yr^{-1}. Using these higher rates, the wind power of a typical WR star is $\sim 10^{38}$ erg s^{-1}. If the WR phase lasts for 4 $\times 10^5$ years, as evolutionary calculations indicate, then the total kinetic energy of a WR wind is $\sim 10^{51}$ ergs, also comparable to the kinetic energy of a supernova remnant.

GLOBAL INPUT OF MATTER AND ENERGY BY STELLAR WINDS

Input Data

Estimates of the total rate of kinetic energy and matter injected, per unit surface area of the galactic disk for the solar vicinity, have been made by Abbott (1982a), Abbott *et al.* (1986), Van Buren (1985), and van der Hucht, Williams, and Thé (1987). In order to determine such global averages, the following information is required:

(1) Catalogs of hot stars. For OB stars, the catalog of Garmany, Conti, and Chiosi (1982) is ~90% complete to a distance of 3 kpc. For the WR stars, the work of van der Hucht *et al.* (1981, 1988) is also essentially complete to about 3 kpc. These catalogs can be used to derive the surface density of stars in each spectral type and luminosity class.

(2) Evolutionary models. Models are generally used to infer the initial masses, main sequence lifetimes, luminosities, effective temperatures, and surface abundances for the individual stars from the catalogs cited above. There has been much progress recently in evolutionary calculations for massive stars. It has been realized that mass loss itself can significantly alter the evolution of a massive star (cf. Chiosi and Maeder 1986). Together with improvements in treatment of physical processes like convection (e.g., "overshooting"), an optimist can believe that stellar parameters can be reliably inferred from observational data coupled with evolutionary models.

(3) A calibration of $\dot{M}$ against other stellar parameters. It was noted above that the best correlation seems to be between $\dot{M}$ and L, and that other parameterizations, in terms of M_*, R_*, etc., give no better fit to the observations.

(4) A calibration of V_∞ against other stellar parameters, e.g., V_{esc} and T_{eff}, as discussed above.

Calculations of Input Rates

Abbott (1982a) and Abbott *et al.* (1986) have used these four categories of information to compute the mass, kinetic energy, and momentum fluxes from winds for the catalogued OB and WR stars within 3 kpc of the sun, using the data of Garmany, Conti, and Chiosi (1982) and van der Hucht *et al.* (1981), and have derived the average rates per kpc^2 for these quantities. A comparison of energy, momentum, and mass inputs by stellar category showed that:

1. The O-stars dominate both the radiative luminosity and the ionizing flux–not a surprising result.

2. The WR star winds contribute about half of the mass, momentum, and kinetic energy deposited in the ISM by stellar winds, a conclusion which was not previously appreciated.

3. The stellar wind kinetic energy return is dominated by the most luminous stars (early-O and WR). This result is mainly a consequence of the rather steep luminosity dependence of $\dot{M}$, though there is a corollary tendency for the most luminous stars to have the highest wind velocities. (There are notable exceptions, however, such as the very luminous B1 star P Cyg, which has a very low wind velocity of 220 km s^{-1}.)

Van Buren (1985) has also determined mass and energy return rates for winds of OB stars. He redetermined the luminosity function and derived an IMF, including a correction for extinction, which was significantly flatter than that of Garmany, Conti, and Chiosi (1981). Applying this IMF and a somewhat different calibration of $\dot{M}$ and V_∞ in terms of stellar parameters, Van Buren (1985) obtained mass and kinetic energy return rates for OB stars which were significantly higher than Abbott's (1982a) values, as summarized in Table 1.

Table 1: Comparison of Mass and Kinetic Energy Return Rates Calculated for OB Stars

Quantity	Van Buren (1985)	Abbott (1982)	
Mass	2.6×10^{-4}	8.6×10^{-5}	$M_\odot$ yr^{-1} kpc^{-2}
Kinetic Energy	5.4×10^{38}	1.0×10^{38}	erg s^{-1} kpc^{-2}

The discrepancy is mainly a consequence of Van Buren's relatively flat IMF, which implies a higher density of the most massive, and therefore most luminous, stars, which dominate the mass and energy return. There is at present no obvious resolution of this discrepancy, though the OB star catalog of Garmany, Conti, and Chiosi (1981) is probably missing no more than 10% of all O-stars within 3 kpc of the sun. It seems possible, therefore, that Van Buren's extinction correction may have somewhat overestimated the density of the most luminous stars.

The survey of Abbott *et al.* (1986) confirmed the importance of WR winds as sources of enriched matter and of kinetic energy to the ISM. However, van der Hucht, Cassinelli, and Williams (1986) have argued that revised surface abundances of WR stars (especially the WC spectral type) predicted by Prantzos *et al.* (1986) should be used to compute WR mass loss rates and wind composition. These revised abundances, with substantial increases in CNO abundances over those assumed by Abbott *et al.* (1986), yield significantly higher mass loss rates, by factors of ~2 for the WN type and ~3 for the WC type. As a consequence, van der Hucht, Cassinelli, and Williams (1986) find that the WR stars are even more important as sources of matter and energy for the ISM than was previously believed. Table 2 summarizes the estimated return rates by stellar category: O-stars, WR stars, and B and A supergiants. The rates for O-stars and BA supergiants are from Abbott (1982) while the WR star rates are the revised values of van der Hucht, Cassinelli, and Williams (1986).

Table 2: Comparison Of Stellar Inputs By Category
(averages for D < 3 kpc)

Quantity	%-contribution by WR	O	BA	Total Rate (kpc^{-2})
Mass	77%	19%	4%	1.6×10^{-4} $M_\odot$ yr^{-1}
K.E.	70	28	2	3.2×10^{38} erg s^{-1}
Momentum	74	23	3	2.3×10^{30} g cm s^{-1}
Rad. Lumin.	8	65	27	3.5×10^{40} erg s^{-1}
Ion. Photons	5	93	2	3.0×10^{50} s^{-1}

Sources:
(1) O stars, B and A supergiants: Abbott 1982
(2) WR stars: van der Hucht, Cassinelli, & Williams 1986

Element Enrichment

As indicated in Table 2, the derived rate of mass returned by hot star winds to the ISM is $\sim 1.6 \times 10^{-4}$ $M_\odot$ yr^{-1} kpc^{-2}, with an uncertainty of at least a factor of two. Some part of this material is enriched in nucleosynthesis products. Because of their highly evolved state, the WR stars dominate the chemical enrichment of the ISM by the hot star winds. Following Abbott (1982) but using the revised abundances of van der Hucht, Cassinelli, and Williams (1986), we can estimate the yield of He and the CNO elements by the WR star winds. The "yield", Y_M, is defined here as the mass of element M by which the ISM is enriched per unit mass of the ISM which is formed into stars. If X_M is the relative mass fraction of element M, then we calculate

$$Y_M = [(\Delta X_M(\mathrm{WN}) \times \dot{M}_{\mathrm{WN}}) + (\Delta X_M(\mathrm{WC}) \times \dot{M}_{\mathrm{WC}})]/SFR$$

with separate terms for the WN and WC spectral types, and where $\Delta X_M = X_M(\mathrm{WR}) - X_M(\mathrm{ISM})$. With the abundances and mass loss rates of van der Hucht, Cassinelli, and Williams (1986) and a star formation rate, SFR, of 4×10^{-3} $M_\odot$ yr^{-1} kpc^{-2} (probably close to a lower limit–see Jura 1987), the yields of He, C, N, and O for the WN and WC spectral types are summarized in Table 3. For the assumed values, the table indicates that almost 1 $M_\odot$ of CNO elements is returned to the ISM for every 100 $M_\odot$ converted to stars. Compared with the enrichment yields expected for supernovae (cf. Chiosi and Maeder 1986), the WR star winds are estimated to produce $\geq$60% of the total yield of He and $\geq$15% of the yield of the CNO elements. Thus, the WR star winds are the dominant source of helium and a non-negligible source of C, N, and O for the enrichment of the interstellar medium.

Table 3: Element Enrichment by Wolf-Rayet Star Winds

	Relative Mass Fractions			
Element	X(WN)	X(WC)	X(ISM)	Yield
He	0.95	0.32	0.22	1.4×10^{-2}
C	.00037	.39	.0034	5.2×10^{-3}
N	.021	.00	.0012	3.3×10^{-4}
O	.0011	.25	.0082	3.1×10^{-3}
CNO	.022	.64	.013	8.6×10^{-3}

Note: mass loss rates and mass fractions for the WN and WC spectral categories are from van der Hucht, Cassinelli, and Williams (1986)

"LOCAL" EFFECTS OF STELLAR WINDS ON THE ISM

Standard Model of Wind-Blown Bubbles

The standard picture of the interaction of a high-velocity wind with the ambient medium has been developed by a number of workers. Avedisova (1972) proposed a model, based on the Sedov solution for supernova shocks, to explain certain ring nebulae associated with WR stars (e.g., NGC 6888). Related work was published by Steigman, Strittmatter, and Williams (1975) and by Castor, McCray, and Weaver (1975), who considered an adiabatic similarity solution for wind-blown shells expanding into a uniform medium. These models predict the radius and velocity of the shell as a function of time. An improved analytical model was developed by Weaver *et al.* (1977) to include the effects of radiative losses at later times. The basic prediction of the model is that the high-velocity stellar wind will drive a shock wave into the ambient gas to produce three concentric zones: (1) the stellar wind itself, with a velocity of ~2000 km s^{-1}, density falling as $1/r^2$, and a temperature of ~10^4 K; (2) outside this region, a shocked stellar wind with nearly constant density and a decelerating velocity field, and with a temperature of 10^6 - 10^7 K; and (3) an outer shell of high-density shocked interstellar gas, with T $\approx 10^4$ K.

These analytical results are in good agreement with recent numerical hydrodynamic calculations by Tenorio-Tagle *et al.* (1989) for a "standard model" wind-blown shell, which develops precisely the structure predicted by the analytic model of Weaver *et al.* (1977).

A number of wind-blown bubble candidates have been identified. The X-ray "supershell" in Cygnus (Cash *et al.* 1980) has been suggested as a bubble blown by the collective effect of winds from members of the Cyg OB2 association (Abbott, Bieging, and Churchwell 1981). The total thermal energy content of the bubble is $\sim 6 \times 10^{51}$ ergs, while the wind luminosity of stars in Cyg OB2 (on which the bubble is centered) is $> 2 \times 10^{52}$ erg Myr^{-1}. The energetics and estimated age of the bubble are consistent with a wind-blown origin.

Some of the giant H I shells catalogued by Heiles (1979) are probably produced by stellar winds. The size and energy requirements of such shells can be explained by one or a few early-O star winds. Heiles has noted a possible association of the H I shells with young clusters.

Finally, a number of ring-shaped nebulae may be formed, or strongly influenced by, stellar winds. Obvious examples include the Rosette and Bubble (NGC 7635) Nebulae, and ring nebulae associated with Wolf-Rayet stars (Avedisova 1972; Chu 1981).

Effects of a Cloudy Medium

The standard model for wind-blown bubbles is unrealistic, since it assumes that the wind expands into a homogeneous medium. In fact, the ISM is full of clouds and density variations. The effects of such structure on wind-blown bubbles can be substantial. McKee, Van Buren, and Lazareff (1984) considered a cloudy medium around an O-star, with a cloud mass spectrum $N(M) \sim M^{-2}$. They argue for the importance of two physical effects in the development of a bubble: (1) "photoevaporation", by which photoionization removes material from neutral clouds, thereby increasing the density and mass of the H II region (cf. Elmegreen 1976, who modelled an ensemble of uniform clouds); and (2) the "rocket effect", which displaces the clouds away from the ionizing star. These two effects result in a "homogenization" of the cloudy medium out to a radius R_h which depends on the initial mean density of the ambient gas, n_m, as $R_h = 56 n_m^{-0.3}$ pc. Remarkably, R_h is virtually independent of the stellar lifetime. The mass displaced (i.e., the mass of the swept-up shell) is predicted to be $M_h = 2.4 \times 10^4 n_m^{0.1}$ $M_\odot$, nearly independent of the initial mean density. The effect of the cloudy medium on the bubble depends on the mechanical luminosity, L_W ($\equiv \dot{M} V_\infty^2/2$) of the wind. If

$$L_W < L_{crit} = 1.3 \times 10^{36} (S_{49}/n_m)^{1/3} \text{ erg s}^{-1}$$

(where S_{49} is the stellar ionizing flux in 10^{49} photons s^{-1}, and n_m is in cm^{-3}), then the bubble expands into the homogenized medium around the star as described by the standard model discussed above. If $L_W \geq L_{crit}$, the bubble expands until it reaches the homogenization radius, R_h. At this point cloud evaporation "poisons" the bubble: rapid radiative cooling reduces the bubble to a momentum conserving expansion and the bubble stalls. Thereafter, the expansion of the bubble is controlled by cloud evaporation, so that $R_{bubble} \approx R_h$.

McKee, Van Buren, and Lazareff (1984) argue that a classification scheme suggested by Chu (1981) to categorize WR nebulae, and used also by Lozinskaya

(1982) for O-star nebulae, can be explained as an evolutionary sequence of wind-blown bubbles in cloudy media. The stages of development are:

(1) Wind blown shell. This is the earliest stage, with the shell size comparable to that of the H II region.

(2) Amorphous H II region. A thick shell is dominated by the photoionization of clouds. The effects of this process on the clouds have recently been calculated by Bertoldi (1989) and Bertoldi and McKee (1990), who conclude that small clouds are entirely evaporated, while large clouds are first imploded, then accelerated away from the star by the rocket effect. Observational examples of such imploded clouds may be the globules seen in many optical H II regions (e.g., Rosette, Gum).

(3) Ring-like H II regions. When the homogenization radius exceeds the Strömgren radius, the nebula is a thin shell of H II filled by the (low-density) wind bubble.

(4) Invisible. For late-type O-stars near the end of the main sequence lifetime, the emission measure of the bubble is too low to be readily detectable.

(5) Stellar ejecta. After the star leaves the main sequence, the nebular gas near the star is expected to be entirely wind material. Examples include the ring nebulae associated with WR stars studied by Chu, Treffers, and Kwitter (1983 and references therein).

Supernova Remnants in Wind-Blown Bubbles

All early-type stars capable of producing stellar wind-blown bubbles should end their evolution as type II supernovae. What is the effect of the pre-existing bubble on the evolution of the supernova remnant (SNR)? This is an important point, because the initial ambient conditions of the remnant expansion are very different for a wind-blown bubble ($n \sim 0.01$ cm^{-3}, $T \sim 10^4 - 10^6$ K) as compared with the usually assumed values (e.g., $n = 1$ cm^{-3}, $T = 100$ K). McKee, Van Buren, and Lazareff (1984) point out that in such a case, the SNR will interact only with the stellar wind ejecta out to $R \approx 20$ pc. Since the mass of the SNR should be comparable to the mass of the stellar ejecta within this radius, the SNR remains essentially in free expansion out to $R \approx 20$ pc, and does not go into the Sedov-Taylor phase.

Recent one-dimensional numerical hydrodynamic calculations by Tenorio-Tagle *et al.* (1989) support this picture. These authors have modelled a supernova event of kinetic energy 10^{51} ergs occurring within a wind-blown shell, for a wind with $V_\infty = 1000$ km s^{-1}, $\dot{M} = 3 \times 10^{-5}$ M$_\odot$ yr^{-1}, and a bubble age of 2×10^5 yr. These wind parameters are reasonable for a WR wind (though with a V_∞ somewhat lower than is typical). They describe two model cases:

(1) Mass in the wind-blown shell is comparable to that of the SN ejecta. In this case, the transmitted shock outruns the wind-blown shell and proceeds into the undisturbed gas, forming a second outer shell. The predicted X-ray size of the SNR should then exceed the Hα size (from the shocked shell). The SNR expands freely at first, to reach the Sedov phase in only ~20% of the time required for the standard (non-wind) case.

(2) Mass in the wind-blown shell is much larger than the mass of the SNR. In this case the SN shock compresses and accelerates the wind shell, but radiative losses prevent the remnant from entering the Sedov phase at all. Instead, the shell goes directly into the momentum-conserving phase. The SN

shock is trapped in the massive outer wind shell and cannot move ahead into the undisturbed gas.

The results of Tenorio-Tagle *et al.* (1989) imply these consequences for SNR evolution in a wind-blown bubble:

—The remnant develops multiple-shell structure, due to the presence of reverse shocks.

—The SN shock quickly expands to reach the wind shell.

—As a result, the ages of SNR's derived from the assumption of a long Sedov phase may be overestimated by a factor of several.

—Wind-blown bubbles may account for the early optical emission from SNR's.

SUMMARY

This paper has reviewed the properties of winds from hot (OB and WR) stars and examined the effects of these winds both on the global input of energy and matter into the ISM, and on the local effects of wind-blown bubbles on photoionized nebulae and on supernova remnant evolution. Significant conclusions are:

(1) The total kinetic energy injected into the ISM by the wind of a luminous OB or WR star is comparable to that from a Type II supernova.

(2) WR star winds dominate both the element enrichment and the kinetic energy returned by all hot star winds, in a global average.

(3) The standard model of stellar wind-blown bubbles (e.g., Weaver *et al.* 1977) evidently requires substantial modification in a cloudy ISM.

(4) Wind-blown bubbles will significantly affect the evolution of a subsequent supernova remnant, in particular by greatly shortening (or eliminating) the Sedov phase.

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