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INTERSTELLAR BUBBLES

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ABSTRACT

Early-type stars blow bubbles in the interstellar medium. The radii of the bubbles are typically 30 pc. Typical conditions in their interiors are $T \approx 10^6$ K and $n \approx 0.01$ cm^{-3}. The dense shell of swept-up interstellar gas that surrounds them is likely to trap the ionization front and may also have an outer layer of H_2. The column density of O VI in the interior is in accord with observations by the *Copernicus* ultraviolet telescope.
Subject headings: gas dynamics — interstellar matter — stellar winds

I. INTRODUCTION

Optical (Conti and Leep 1974) and ultraviolet (Morton 1967; Smith 1970) observations show that stars of spectral type earlier than B2 have strong stellar winds with terminal velocities of order $V \approx$ 1500–3000 km s^{-1} and rates of mass loss $\dot{M}_w$ approaching 10^{-6} $M_\odot$ yr^{-1}. Such winds can, over the lifetime of the star, impart a mechanical energy of order 10^{50} ergs to the surrounding interstellar medium, which is comparable to estimates of energy in supernova shells (Woltjer 1972), and an order of magnitude greater than the mechanical energy that might be imparted by expansion of the H II region.

Matthews (1966) suggested that the central cavity in the Rosette Nebula might be caused by the action of strong winds from the central stars. Pikel'ner (1968), Pikel'ner and Shcheglov (1969), Avedisova (1972), Dyson and deVries (1972), and Dyson (1973) have studied the interaction of strong stellar winds with the surrounding interstellar gas, and have shown that the stellar wind will sweep up a thin, dense circumstellar shell. More recently, Steigman, Strittmatter, and Williams (1975) have calculated models for ionization of the shell that agree reasonably well with the *Copernicus* ultraviolet observations of trace elements for the case of ζ Oph. Indeed, there is ample evidence for thin, dense sheets in front of early-type stars. Herbig (1968) inferred a thin ($\lesssim$0.15 pc), dense ($n \gtrsim 500$ cm^{-3}) sheet in front of ζ Oph to account for optical interstellar lines, a result substantiated by ultraviolet observations of this star (Morton 1975; deBoer and Morton 1975). Also, Black and Dalgarno (1973) and Jura (1975*a*, *b*) have analyzed *Copernicus* ultraviolet observations of H_2 rotational excitation to infer thin, dense sheets in front of several other early-type stars.

We have studied the interaction of a strong stellar wind with the surrounding interstellar gas, and have found that thin, dense circumstellar shells will develop around early-type stars, as suggested by the above authors. We find further that there is a transition region dominated by thermal conduction between the cold shell and the hot ($\sim 10^6$ K) shocked stellar wind interior to the shell. This interior has a column density N(O VI) $\approx 10^{13}$ cm^{-2}. It provides a natural interpretation for the *Copernicus* observations of O VI absorption in early-type stars (Jenkins and Meloy 1974), one that we feel is more convincing than their interpretation in terms of hot, low-density interstellar regions.

In this *Letter* we sketch the evolution of circumstellar shells swept up by stellar winds, and show how the observed O VI column densities follow from the theory. We also show that the ionization front is likely to be in the shell, and suggest that the shell may have an outer layer of H_2 and other molecules. Details of the dynamical structure and evolution of the shells and discussion of further observational consequences will be presented in a subsequent paper (Castor, McCray, and Weaver 1975, hereafter Paper II).

II. EVOLUTION OF A CIRCUMSTELLAR SHELL

The evolution of a wind-driven circumstellar shell is analogous to that of a supernova shell (cf. Spitzer 1968; Woltjer 1972); there is an initial phase of free expansion at the wind velocity lasting for a few centuries, a phase of adiabatic expansion lasting a few thousand years, a "snowplow" phase in which the swept-up interstellar gas collapses into a thin, cold shell as a result of radiative cooling (Cox 1972), and finally, if the star lasts long enough, a phase in which the shell dissipates into the surrounding medium as the flow tends to a steady state. Here we describe only the snowplow phase, which occupies most of the lifetime of the star.

During this phase the system has a four-zone structure consisting of (a) innermost, a hypersonic stellar wind with $\rho_w(R) = \dot{M}_w/4\pi R^2 V$; (b) next, a hot, almost isobaric region consisting of shocked stellar wind mixed with a small fraction of the swept-up interstellar gas; (c) a thin, dense, cold shell at radius R_s expanding at velocity $\dot{R}_s$ and containing most of the swept-up

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interstellar gas; (d) ambient interstellar gas of density ρ_0. The stellar wind adds energy to region (b) at a rate $\dot{E}_0 = (1/2)\dot{M}_w V^2$, either in a collisionless shock at some $R_1 \ll R_s$, or by Coulomb stopping of wind ions in region (b). The dominant energy loss of region (b) is work against the dense shell (c), so that the total energy of region (b) obeys the equation

$$\dot{E}_b = \dot{E}_0 - 4\pi R_s^2 P_b \dot{R}_s \,, \quad (1)$$

with

$$\tfrac{4}{3}\pi R_s^3 P_b = \tfrac{2}{3}E_b = 0.42 \frac{M_b}{\mu} kT_b \,, \quad (2)$$

where M_b is the mass in region (b). We consider a gas of atomic density n with $n_{\rm H} = 0.9n$, $n_{\rm He} = 0.1\, n$, and mass density $\rho = 1.3\, nm_{\rm H}$, which, if fully ionized, has mean molecular weight $\mu = 0.62\ m_{\rm H}$. The kinetic energy of region (b) is negligible. T_b is the temperature near the center of region (b), and the factor 0.42 accounts for the nonuniform density of region (b); cf. § III. The motion of the shell (c) follows from

$$\frac{d}{dt}[M_c(t)\dot{R}_s(t)] = 4\pi R_s^2 P \,, \quad (3)$$

where

$$M_c(t) = \frac{4}{3}\pi \rho_0 R_s^3 \,, \quad (4)$$

assuming that most of the swept-up interstellar mass remains in the shell.

Thermal conduction across the inner boundary of the shell causes gas to "evaporate" from region (c) into region (b), where it mixes with the shocked stellar wind. The mass loss of the shell due to this evaporation is small compared with the gain from sweeping up interstellar gas, but the evaporation dominates the stellar wind as a source of mass for region (b). We show below that the mass gain of region (b) due to evaporation is given approximately by

$$\dot{M}_b = \frac{16\pi}{25}\frac{\mu}{k} C T_b^{5/2} R_s \,, \quad (5)$$

where the thermal conductivity is given by $K(T) = CT^{5/2}$, with $C = 1.2 \times 10^{-6}$ ergs cm^{-1} s^{-1} $K^{-7/2}$ (Spitzer 1962).

Equations (1)–(4) have the solution (cf. Avedisova 1972)

$$R_s(t) = 0.76\left(\frac{E_0 t^3}{\rho_0}\right)^{1/5} = 28\left(\frac{\dot{M}_6 V_{2000}^2}{n_0}\right)^{1/5} t_6^{3/5}\ {\rm pc} \,, \quad (6)$$

where $\dot{M}_6 = \dot{M}_w/(10^{-6}\ M_\odot\ {\rm yr}^{-1})$, $V_{2000} = V/(2000$ km s$^{-1})$, and $t_6 = t/(10^6$ yr). The temperature and atomic density near the center of region (b) are given by

$$T_b = 1.6 \times 10^6 n_0^{2/35} (\dot{M}_6 V_{2000}^2)^{8/35} t_6^{-6/35}\ {\rm K} \,, \quad (7)$$

and

$$n_b = 0.01 n_0^{19/35} (\dot{M}_6 V_{2000}^2)^{6/35} t_6^{-22/35}\ {\rm cm}^{-3} \,. \quad (8)$$

Region (b) emits bremsstrahlung with luminosity

$$L_b = 3.8 \times 10^{33} n_0^{18/35} (\dot{M}_6 V_{2000}^2)^{37/35} t_6^{16/35}\ \ {\rm ergs\ s}^{-1} \,. \quad (9)$$

This is generally insignificant compared with the energy input from the wind, but it may be a significant source of extreme ultraviolet and soft X-rays.

Note that the behavior of equation (6) follows from simple dimensional arguments. It may be compared with the analogous behavior (Woltjer 1972) $R_s(t) = 1.17(E_0 t^2/\rho_0)^{1/5}$ for a supernova shell of energy E_0 in the adiabatic phase. Unlike the supernova shell, the circumstellar shell maintains this behavior in the snowplow phase because much of the energy remains in region (b), which does not radiate efficiently.

Steigman *et al.* (1975) obtained a different law, $R_s(t) = (3\dot{M}_w V t^2/2\pi\rho_0)^{1/4}$, because they assumed that the stellar wind was not stopped until it impacted against the shell (c), so that $p = \rho_w(R_s)V^2 = \dot{M}_w V/4\pi R_s^2$ in equation (3), a value lower than p_b. That assumption is only valid for $t \lesssim 10^3$ yr, when region (b) is thin; it leads to an underestimate of $R_s(t)$ at later times.

One can estimate the time at which the circumstellar shell enters the snowplow phase by equating the radiative cooling time scale of the interstellar gas entering the shell with the age of the system. This occurs approximately when the temperature of the shocked interstellar gas, $T \approx 3\mu\dot{R}_s^2/16k$, is equal to 6×10^5 K, the temperature at which the radiative cooling function $\Lambda(T)$ becomes large (Cox 1972), at a time

$$t \gtrsim 1.7 \times 10^3 \left(\frac{\dot{M}_6 V_{2000}^2}{n_0}\right)^{1/2}\ \ {\rm yr} \,. \quad (10)$$

After this time, the density n_s in the shell is given by

$$n_s = (\mu \dot{R}_s^2/kT_s) n_0$$
$$= 3.2 \times 10^4 \frac{\mu}{m_{\rm H}} (\dot{M}_6 V_{2000}^2)^{2/5} t_6^{-4/5} n_0^{3/5}/T_s\ \ {\rm cm}^{-3} \,, \quad (11)$$

where T_s is the temperature in the shell and $\mu/m_{\rm H} = 0.65$, 1.30, and 2.36, respectively, for H II, H I, and H_2.

The shell has total column density

$$N_s = n_0 R_s/3 \approx 2.9 \times 10^{19} (\dot{M}_6 V_{2000}^2)^{1/5} n_0^{4/5} t_6^{3/5}\ \ {\rm cm}^{-2} \,. \quad (12)$$

The elevated density of the shell makes it likely that the ionization front will be in the shell itself. The H II region in the shell will have $T \approx 8000$ K and column density

$$N_{\rm II} = \min\,[N_s,\ 5.0 \times 10^{14} n_0^2 R_0^3 n_0^{-1/5} \times (\dot{M}_6 V_{2000}^2)^{-4/5} t_6^{-2/5}\ {\rm cm}^{-2}] \,, \quad (13)$$

where R_0 is the Strömgren radius in parsecs that would obtain for the star in a medium of uniform density n_0.

If $N_{\rm II} < N_s$, the shell will also have an outer layer of H I (or H_2) with $T \approx 80$ K and density $\sim$200–400 times that of the H II region. For example, if we assume $\dot{M}_6 V_{2000}{}^2 = 1$ for an O7 star with $n_0{}^{2/3}R_0 = 44$ pc cm^{-2} (Spitzer 1968), we derive the criterion $n_0 t_6 >$ 1.5 for the ionization front to be trapped in the shell. This criterion would be independent of spectral type if $\dot{M}_6 V_{2000}{}^2$ were linear with the stellar luminosity in photons beyond the Lyman limit.

III. THERMAL CONDUCTION AND THE O VI COLUMN DENSITY

Heat flow from region (b) into region (c) causes cold gas to expand into region (b). In order to illustrate this process in a simple way, we assume that the flow from the shell inward is reasonably approximated by a stationary plane-parallel flow. If so, the flow at constant pressure is described by (Zeldovich and Pikel'ner 1969; Penston and Brown 1970)

$$\rho v \frac{dH}{dz} = \frac{d}{dz}\left[K(T)\frac{dT}{dz}\right] - \rho\Lambda(T)\,, \qquad (14)$$

where $z = R_s - R$, $\rho v = \dot{M}_b/4\pi R_s{}^2$, and $H = 5\,kT/2\mu$ is the specific enthalpy. We obtain equation (5) by integrating equation (14) from the shell ($z = 0.\ T \approx 0$) to the center ($z \approx R_s$, $T = T_b$), with the further assumption that the radiative cooling term $\rho\Lambda(T)$ is negligible in the transition zone. The temperature in region (b) obeys the law $T(z) \propto z^{2/5}$, which we write as $T(R) = T_b(1 - R/R_s)^{2/5}$, and the density in region (b) follows from $n(R)T(R) = n_b T_b$. These approximations yield the factor 0.42 in equation (2). Comparison with a detailed solution for nonstationary flow to be described in Paper II shows that the plane-parallel approximation introduces an error $\lesssim$10 percent; the approximation of neglecting the radiative cooling is a more significant one, but we find that the results quoted here are within a factor 2 of the correct ones.

In the transition region, there will be a zone whose temperature $T \approx 3 \times 10^5$ K is such that there is a significant fraction $f_{\rm O\,VI}$ of O VI. The column density is given by $N_{\rm O\,VI} = 0.9 X_{\rm O} \int n(R) f_{\rm O\,VI}(T) dR$, where $X_{\rm O} = 4.4 \times 10^{-4}$ is the fractional abundance of oxygen relative to hydrogen, and $f_{\rm O\,VI}(T)$ has been calculated by Allen and Dupree (1969). Using our approximate expressions for $T(R)$ and $n(R)$, we find

$$N_{\rm O\,VI} = \frac{5}{2} n_b R_s X_{\rm O} T_b{}^{-3/2} \int f_{\rm O\,VI}(T) T^{1/2} dT$$

$$\approx 1.5 \times 10^{13} n_0{}^{9/35} (\dot{M}_6 V_{2000}{}^2)^{1/35} t_6{}^{8/35} \quad {\rm cm}^{-2}\,. \quad (15)$$

Equation (15) gives values which are very insensitive to the assumed parameters and are in good agreement with the O VI column densities in front of early-type stars reported by Jenkins and Meloy (1974).

We have made analogous calculations of the column densities of other highly ionized atoms using the ionization equilibrium calculations by Jordan (1969), and find log $[N(X)/N({\rm O\ VI})] = -0.6, -0.9, -1.1$, and -2.4, respectively, for X = C IV, N V, Si IV, and S IV, assuming cosmic abundances given by Dalgarno and McCray (1972). We note a discrepancy between our results for N V and the observations of York (1974), who finds log $[N({\rm N\ V})/N({\rm O\ VI})] < -1.63$ and < -1.56, respectively, for α Vir and λ Sco. This discrepancy is not unique to our model. Since N V is the dominant ionization stage of nitrogen over the same temperature range in which O VI dominates, the same discrepancy would occur in any hot-gas model for O VI.

IV. DISCUSSION

We believe that our theory provides a natural explanation of the O VI column densities observed with *Copernicus* that is more convincing than the interstellar interpretation advanced by Jenkins and Meloy (1974). On physical grounds the interstellar interpretation seems unlikely, because O VI is found in a temperature range that is forbidden in steady-state models for heating of the interstellar gas (McCray and Buff 1972) and that is least likely in time-dependent models because it is near the maximum of the cooling function $\Lambda(T)$. But more compelling evidence for the circumstellar explanation is provided by the velocities of the observed O VI features. In all but six of the 25 cases reported by Jenkins and Meloy,[1] the velocity of the O VI feature is blueshifted relative to the star, typically by 10–20 km s^{-1}, as would be derived from equation (6) with $t \approx 10^6$ yr. Further, the data show that the O VI feature is usually less blueshifted relative to the later-type stars, as would be expected because the later stars are on the average older.

Beyond explaining the O VI observations, our theory has major implications regarding the structure and dynamics of H II regions around early-type stars that are subject to a variety of observational tests. For example, the data on optical and radio line emission, and on radio and infrared continuum emission from H II regions, should be examined carefully with the aim of distinguishing between the shell sources we predict and more uniform emitting regions. It might be possible to observe region (b) as a weak, extended source of extreme ultraviolet or soft X-rays. The likelihood that the dense shell traps the ionization front implies that the radii of H II regions may differ substantially from those calculated for a uniform-density medium, and that the development of the late stages of an expanding H II region (cf. Spitzer 1968) will be modified.

Perhaps the most interesting implication of our theory is the likelihood of molecules in the outer part of the shell. Even in the comparatively low-density interstellar environment observed by the *Copernicus* ultraviolet telescope, there is evidence (Black and Dalgarno 1973; Jura 1975*a*, *b*) for sheets of H_2 near early-type stars with densities and column densities

[1] Actually, these numbers are based on unpublished revised determinations of the velocities of the O VI features kindly provided by Dr. Jenkins. In only four cases is the relative O VI velocity significantly positive.

in accord with equations (11) and (12). An important test of our model will be to see whether the velocities of H_2 and HD features agree with the velocities of the blue sides of the O VI features. (The O VI column extends into the interior of region [b], so that its mean wavelength should be somewhat redder.)

A more exotic environment yet is the shell that would be formed around a young (e.g., $t \approx 10^4$ yr) early-type star embedded in a dust cloud (e.g., $n_0 \approx 10^3$ cm^{-3}). Such a shell would certainly have density great enough to permit rapid formation of H_2. The soft X-rays from region (b) would alone give an ionization rate $\zeta \gtrsim 10^{-15}$ s^{-1} in the molecular shell, and subsequent ion-molecule reactions can initiate rapid formation of a large variety of other molecules (cf. Watson 1975). It will be most interesting to consider molecular radio-emission mechanisms in such a shell.

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