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THE HOT, DIFFUSE GAS IN A DENSE CLUSTER OF MASSIVE STARS

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ABSTRACT

We present an analytic model describing the "cluster wind" flow that results from the multiple interaction of the stellar winds produced by the stars of a dense cluster of massive stars. The analytic solution (obtained by matching an inner and an outer solution at the radius of the stellar cluster) can have asymptotically subsonic or supersonic behavior, the latter possibility being appropriate for the case of a cluster surrounded by a low-pressure environment. We also present a three-dimensional numerical simulation of such a cluster wind. We find that the behavior of the mean flow computed from the numerical simulation quite closely follows the flow properties deduced from the analytic model. Finally, we discuss the observational properties of the cluster wind produced by dense clusters such as the "Arches" cluster close to the center of our Galaxy. In particular, we predict that the X-ray emission from the intracluster gas in this stellar cluster could be detectable.

Subject headings: hydrodynamics — shock waves — stars: winds, outflows

1. INTRODUCTION

The recently discovered "Arches" cluster (G0.121+0.017: Nagata et al. 1995; Cotera et al. 1996; Serabyn, Shupe, & Figer 1998) has about 100 massive stars within a ~ 0.2–0.3 pc radius, resulting in a mean separation between stars of ~ 0.1 pc. Such dense clusters of massive stars must have strong multiple stellar wind interactions, resulting in the formation of stellar wind shocks of complex morphologies. The hot, shocked stellar wind should then participate in an outward-directed "cluster wind," which eventually leaves the stellar cluster. This diffuse component may be detectable in addition to the compact emission associated with the stars.

In this paper, we present an analytic model for such a cluster wind, based on the general "mass-loaded wind" approach developed by Dyson and collaborators (see, e.g., Hartquist et al. 1986; Dyson 1992; see also Lizano et al. 1996). This group has studied problems of winds that incorporate material from embedded mass sources in different situations, for example, including the effects of magnetic fields (Williams, Dyson, & Hartquist 1999) and considering three-dimensional spatial distributions of mass sources (Redman, Williams, & Dyson 1998). Analytic models describing the details of the process of mass incorporation from a clump into a wind have been developed by Arthur & Lizano (1997).

Our analytic, cluster wind model differs from the previous work in that the wind itself is generated through the mass-loading process, but is essentially the same as the model presented by Chevalier & Clegg (1985). These authors studied the problem of a wind from a starburst galaxy nucleus driven by the supernovae present in the nucleus. In the present case, the injection of mass and energy from the multiple stellar winds generate a "cluster wind" flow with zero velocity at the center of the cluster, accelerating outward toward the outer boundary of the cluster. The analytic solution for this flow is described in § 2.

We also carry out a full, three-dimensional numerical simulation of a cluster with 30 stars and carry out a comparison of the resulting flow with the analytic model in § 3. Previous numerical simulations of mass-loaded flows have included detailed treatments of the atomic processes (Arthur, Dyson, & Hartquist 1994), but have included the injection of mass only as a parameterized source term (see, e.g., Arthur & Lizano 1997). As far as we are aware, our present numerical simulation represents the first calculation to incorporate a complete, three-dimensional, nonparameterized treatment of the mass incorporation process.

In § 4, we discuss the radiative properties of the cluster wind and describe the possible observational characteristics of this flow. Finally, we summarize our results in § 5.

2. ANALYTICAL CONSIDERATIONS

We consider a cluster of N identical stars inside a sphere of radius R_c. The stars are uniformly distributed with a number density

$$n = \frac{3N}{4\pi R_c^3} . \tag{1}$$

Each star has an identical wind with a mass-loss rate $\dot{M}_w$ and (terminal) velocity V_w. Alternatively, one could consider an ensemble of N stars with different winds with mass-loss rates $\dot{M}_i$ and velocities $V_{w,i}$ by defining an average mass-loss rate $\dot{M}_w = \sum_{i=1}^{N} \dot{M}_i/N$ and $V_w = (\sum_{i=1}^{N} \dot{M}_i V_{w,i}^2/N\dot{M}_w)^{1/2}$.

Initially, the stellar winds collide with the surrounding interstellar medium (ISM) and with each other, and the volume between the stars begins to be filled up with hot, shocked stellar wind. At long enough times, a stationary flow is established in which mass and energy fed in from the stellar winds are advected outward and eventually escape through the outer boundary of the cluster. This situation is shown in the schematic diagram of Figure 1.

In the steady "cluster wind" flow configuration, for an arbitrary distance R from the center of the cluster, mass and energy conservation imply that

$$\frac{4\pi}{3} R^3 n \dot{M}_w = 4\pi R^2 \rho V , \tag{2}$$

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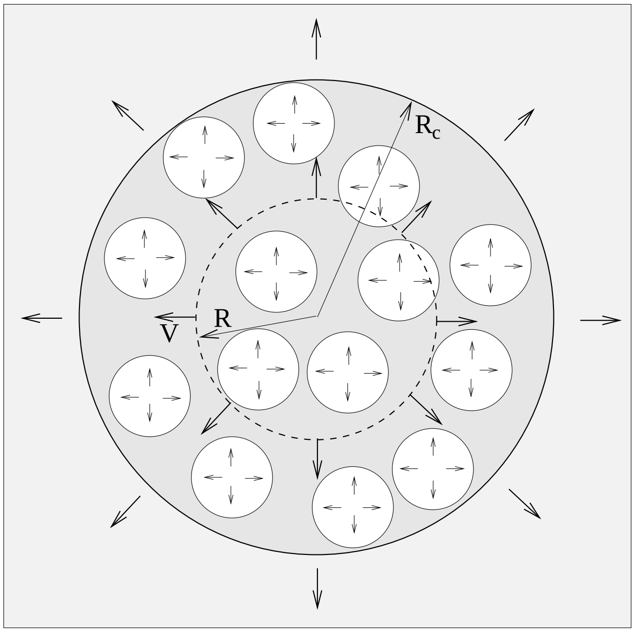

FIG. 1.—Schematic diagram showing the wind-wind interaction that takes place in a dense stellar cluster. The stars are uniformly distributed within the outer radius R_c of the cluster. The material ejected from the stars goes through "stellar wind shocks" (which are schematically drawn as circles, but which in reality will have complex topologies) and then participates in an outward flow [with mean velocity $V(R)$ and density $\rho(R)$] which eventually leaves the cluster and interacts with the surrounding ISM.

$$\frac{4\pi}{3} R^3 n\dot{M}_w\left(\frac{1}{2} V_w^2\right) = 4\pi R^2 \rho V\left(\frac{1}{2} V^2 + h\right), \tag{3}$$

where ρ and V are the mean density and velocity of the "cluster wind" flow and h is its specific enthalpy,

$$h = \frac{\gamma}{\gamma - 1} \frac{P}{\rho}, \tag{4}$$

where P is the mean pressure of the wind (see Fig. 1).

Equation (2) implies that

$$\rho V = \frac{n\dot{M}_w}{3} R, \tag{5}$$

and the ratio between equations (2) and (3) gives

$$\frac{1}{2} V^2 + h = \frac{1}{2} V_w^2 . \tag{6}$$

Let us now consider the equation of motion for the flow,

$$\rho V \frac{dV}{dR} = -\frac{dP}{dR} - n\dot{M}_w V . \tag{7}$$

We should note that in this equation (as well as in eq. [3]) we have neglected the effects of the gravity force. It is straightforward to show, however, that the effect of gravity is completely negligible for the case of an adiabatic wind-wind interaction in a stellar cluster, as the sound speed of the shocked gas is much higher than the escape velocity from the cluster. Introducing the adiabatic sound speed

$$c^2 = \gamma \frac{P}{\rho}, \tag{8}$$

we can write equations (6) and (7) as

$$c^2 = \frac{\gamma - 1}{2} (V_w^2 - V^2), \tag{9}$$

$$\rho V \frac{dV}{dR} = -\frac{1}{\gamma} \frac{d(\rho c^2)}{dR} - n\dot{M}_w V . \tag{10}$$

Using equations (5) and (9) in equation (10), we then obtain:

$$\left[\frac{(\gamma - 1)V_w^2 - (\gamma + 1)V^2}{(\gamma + 1)V_w^2 + (5\gamma + 1)V^2}\right] \frac{dV^2}{V^2} = 2 \frac{dR}{R}, \tag{11}$$

which can be integrated to obtain

$$v\left[1 + \frac{(5\gamma + 1)}{(\gamma + 1)} v^2\right]^{-(3\gamma+1)/(5\gamma+1)} = Ar, \tag{12}$$

in terms of the dimensionless variables

$$v \equiv V/V_w, \quad r \equiv R/R_c . \tag{13}$$

In equation (12), A is an integration constant. Note that this equation correctly gives $v = 0$ for $r = 0$.

Equation (12) then gives the velocity of the flow as a function of radius. However, the constant A remains to be determined. As we will show in the following, the value of this constant is determined by the conditions imposed by the ISM surrounding the cluster.

Outside the cluster $n = 0$, and the mass conservation equation now is

$$\dot{M} \equiv \frac{4\pi}{3} R_c^3 n\dot{M}_w = 4\pi R^2 \rho V, \tag{14}$$

where $\dot{M}$ is the mass-loss rate through the outer boundary of the cluster. Substituting equations (9) and (14) into equation (10) (with $n = 0$) and integrating, we obtain

$$v(1 - v^2)^{1/(\gamma-1)} = \frac{B}{r^2}, \tag{15}$$

where B is a constant.

As $r \to \infty$, equation (15) implies that either $v \to 0$ (asymptotically subsonic flow) or $v \to 1$ (asymptotically supersonic flow). The corresponding limits for the density, sound speed, and pressure are

$$\rho = \frac{\dot{M}}{4\pi B R_c^2 V_w}, \tag{16}$$

$$c^2 = \frac{(\gamma - 1)}{2} V_w^2, \tag{17}$$

$$P = \frac{(\gamma - 1)}{2\gamma} \frac{\dot{M} V_w}{4\pi B R_c^2} \tag{18}$$

for the subsonic solution and

$$\rho = c^2 = P = 0 \tag{19}$$

for the supersonic solution.

Let P_∞ be the pressure of the surrounding ISM, far away from the cluster. For the subsonic solution, the asymptotic pressure given by equation (18) must coincide with P_∞. Therefore, the constant B is given by

$$B = \frac{(\gamma - 1)}{2\gamma} \frac{\dot{M} V_w}{4\pi R_c^2 P_\infty} . \tag{20}$$

The velocity of the flow at the outer boundary of the cluster (i.e., at $r = 1$) follows from equation (15),

$$v_1(1 - v_1^2)^{1/(\gamma-1)} = B \,, \tag{21}$$

and the constant A follows from equation (12),

$$A = v_1\left[1 + \frac{(5\gamma + 1)}{(\gamma - 1)}\, v_1^2\right]^{-(3\gamma+1)/(5\gamma+1)} . \tag{22}$$

The left-hand side of equation (12) has a maximum value of

$$\left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/2}\left(\frac{2}{\gamma + 1}\right)^{1/(\gamma-1)} \quad \text{for } v = \left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/2} . \tag{23}$$

It is then clear from equation (20) that if

$$P_\infty < \frac{1}{\gamma}\left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/2}\left(\frac{\gamma + 1}{2}\right)^{\gamma/(\gamma-1)} \frac{\dot{M} V_w}{4\pi R_c^2} \,, \tag{24}$$

the subsonic solution is not possible. If condition (24) is satisfied, the flow must adopt the supersonic solution. In this case, the flow is actually disconnected from the outside conditions, and the constants A and B adopt their limiting values

$$A = \left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/2}\left(\frac{\gamma + 1}{6\gamma + 2}\right)^{(3\gamma+1)/(5\gamma+1)} , \tag{25}$$

$$B = \left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/2}\left(\frac{2}{\gamma + 1}\right)^{1/(\gamma-1)} \tag{26}$$

for any outside pressure that satisfies the condition given by equation (24). The flow then leaves the boundary of the cluster at the local sound speed,

$$v_1 = \frac{c}{V_w} = \left(\frac{\gamma - 1}{\gamma + 1}\right)^{1/2} , \tag{27}$$

and is monotonically accelerated up to $v = 1$ ($V = V_w$) for $r \to \infty$.

It can be shown that this supersonic solution coincides with the solution found by Chevalier & Clegg (1985), which is given in terms of the Mach number, $M = V/c$, using the relation

$$v^2 = \frac{(\gamma - 1)M^2}{2 + (\gamma - 1)M^2} . \tag{28}$$

Near the center of the cluster ($r \ll 1$ and $v \ll 1$), equation (12) gives

$$v \approx Ar . \tag{29}$$

We can use equations (5), (8), and (9) to obtain the central values

$$\rho_0 = \frac{\dot{M}}{4\pi A R_c^2 V_w} \,, \tag{30}$$

$$c_0^2 = \frac{(\gamma - 1)}{2} V_w^2 \,, \tag{31}$$

$$P_0 = \frac{(\gamma - 1)}{2\gamma} \frac{\dot{M} V_w}{4\pi A R_c^2} . \tag{32}$$

Assuming an abundance of 0.1 for He and that hydrogen is ionized and helium singly ionized, we can use equations (30) and (31) to derive the central hydrogen density and temperature,

$$\left(\frac{n_0}{\text{cm}^{-3}}\right) = \frac{2.28 \times 10^{-2}}{A} N\left(\frac{\dot{M}_w}{10^{-5}\, M_\odot \text{ yr}^{-1}}\right) \times \left(\frac{v_w}{1000 \text{ km s}^{-1}}\right)^{-1}\left(\frac{R_c}{\text{pc}}\right)^{-2} , \tag{33}$$

$$\left(\frac{T_0}{\text{K}}\right) = 1.55 \times 10^7\left(\frac{V_w}{1000 \text{ km s}^{-1}}\right)^2 , \tag{34}$$

where in equation (33) we have substituted $\dot{M} = N\dot{M}_w$. We discuss a numerical example of this solution in the following section.

3. NUMERICAL RESULTS

We have carried out a numerical simulation of a multiple stellar wind interaction problem with the three-dimensional "yguazú" code, which is described in detail by Raga et al. (1999). If we want to simulate a structure similar to the one of the Arches cluster (see § 1), we need to consider $\sim$100 stellar wind sources. As this number is excessive for the limited spatial resolution that we can obtain in three-dimensional gasdynamic simulations, we reduce the problem in the following way.

We assume that the distribution of stars in the cluster has eight octants which have mirror symmetry with respect to the contiguous octants. In this way, we can carry out a numerical simulation of only a single octant, imposing reflection conditions on the planes that separate it from the contiguous octants. In the octant that we consider, we introduce five stars, with winds with the characteristics listed in Table 1. As a result of the reflection symmetry between the octants, these five stars actually represent a total number of 30 stars for a full, spherical cluster. This number of stars is only a factor of $\sim$3 lower than that of the Arches cluster (see Serabyn et al. 1998), but still allows us to resolve the individual wind-wind interactions in our numerical simulation.

The numerical simulation is adiabatic and has been carried out in a uniform, $90 \times 90 \times 90$ Cartesian grid with a spatial resolution of 9×10^{15} cm. It is assumed that the gas has a hydrogen fraction of 0.9 and a helium fraction of 0.1 (by number) and that both H and He are singly ionized. Three of the boundary planes have reflection conditions (see above), and the other three boundary planes have free outflow conditions. We impose the wind outflow conditions on spherical surfaces of 5×10^{16} cm radius centered on the positions of the stellar wind sources (see Table 1). We assume that on these spherical surfaces all of the winds have a temperature of 10^6 K and that the region internal to the surfaces has a constant velocity wind with a number density

TABLE 1

PROPERTIES AND POSITIONS OF THE STELLAR WIND SOURCES

Number of Stars[a]	$\dot{M}_w$ ($\dot{M}_\odot$ yr^{-1})	V_w (km s^{-1})	x (10^{17} cm)	y (10^{17} cm)	z (10^{17} cm)
2	1.0×10^{-5}	1000	1.50	0.00	0.00
8	0.5×10^{-5}	800	3.75	3.75	3.75
4	0.2×10^{-5}	400	1.50	0.00	2.25
8	1.0×10^{-5}	1000	2.25	1.50	3.00
8	0.7×10^{-5}	900	3.00	2.25	1.50

[a] Number of stars with the given $\dot{M}_w$ and V_w, resulting from the symmetry of the simulation.

proportional to the inverse of the square of the distance to the star.

Initially, the region in between the stars is filled with a tenuous gas of number density $n_{\rm env} = 0.1$ cm^{-3} and temperature $T_{\rm env} = 10^7$ K. This medium is flushed out of the computational grid by the stellar winds, and the resulting flow reaches a final, steady configuration which is independent of the properties of the environmental gas that initially fills the computational domain.

This steady configuration (reached after a time integration of 500 yr) is shown in Figure 2. The top plot of this figure shows the emission measure distribution obtained by integrating the square of the number density along lines of sight parallel to the *y*-axis. From this plot, we see that the emission measure of the regions close to the stellar wind sources dominates by $\sim$4 orders of magnitude over the emission measure of the diffuse gas that permeates the cluster.

The bottom plot of Figure 2 shows line-of-sight integrations of the modulus of the logarithmic pressure gradient. In this plot, the regions with higher values correspond to the projections of the shock surfaces (resulting from the multiple wind interactions) onto the (*x*, *z*)-plane. In this plot, one sees several arched structures which correspond to bow shocks formed in interactions of winds from pairs of stars.

We have computed mean values for the density, pressure, and radial velocity as a function of spherical radius *R*, measured from the (*x*, *y*, *z*) = (0, 0, 0) center of the cluster. The resulting mean velocity, density, and temperature are plotted as a function of *R* in Figure 3.

In order to compare these curves with the results of the analytic model, we compute the mass-loss rate $\dot{M} = 2.04 \times 10^{-4}\ M_\odot$ yr^{-1} (adding the contributions from the individual stars listed in Table 1, noting that the stars appear more than once as a result of the symmetry of the numerical simulation of a single octant) and the mean wind velocity $V_w = (\sum_{i=1}^{N} \dot{M}_i V_{w,i}^2/\dot{M})^{1/2} = 919$ km s^{-1} (where $\dot{M}_i$ and

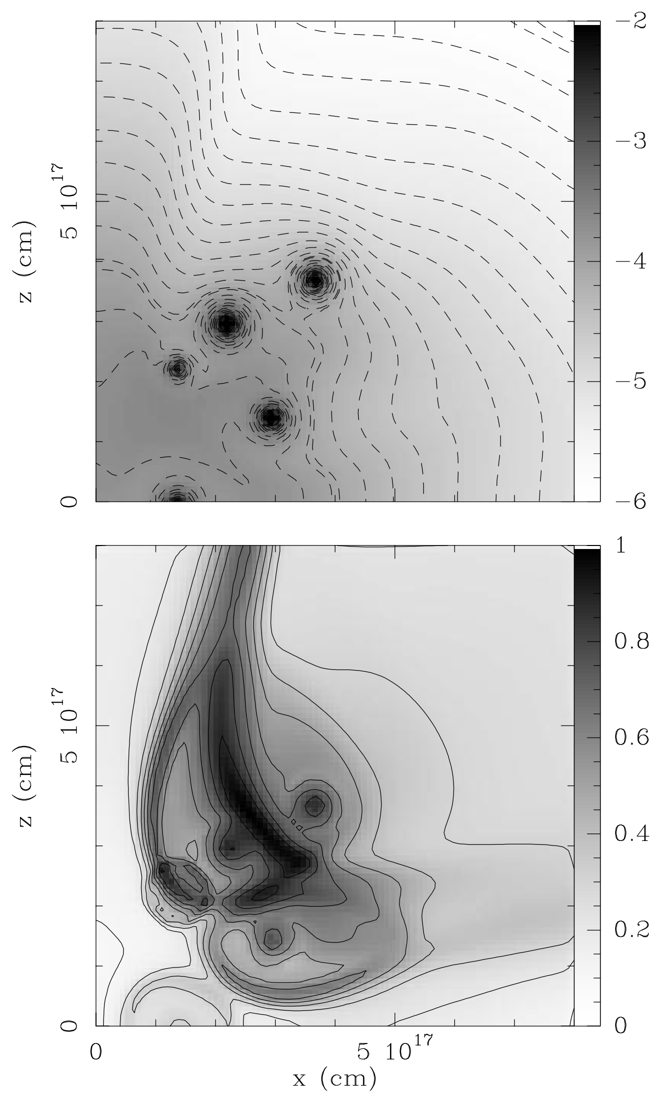

FIG. 2.—Emission measure $\int n^2\,dy$ (*top*) and integrated logarithmic pressure gradient $\int |\nabla(\ln P)|\,dy$ (*bottom*) maps of the stationary solution obtained from the numerical simulation described in the text. *Top*: The emission measure (normalized to a peak value of 1) is depicted with a logarithmic gray scale and with $\sqrt{2}$ contours. *Bottom*: The integrated logarithmic pressure gradient (normalized to a peak value of 1) is depicted with a linear gray scale and with linear contours at intervals of 0.1.

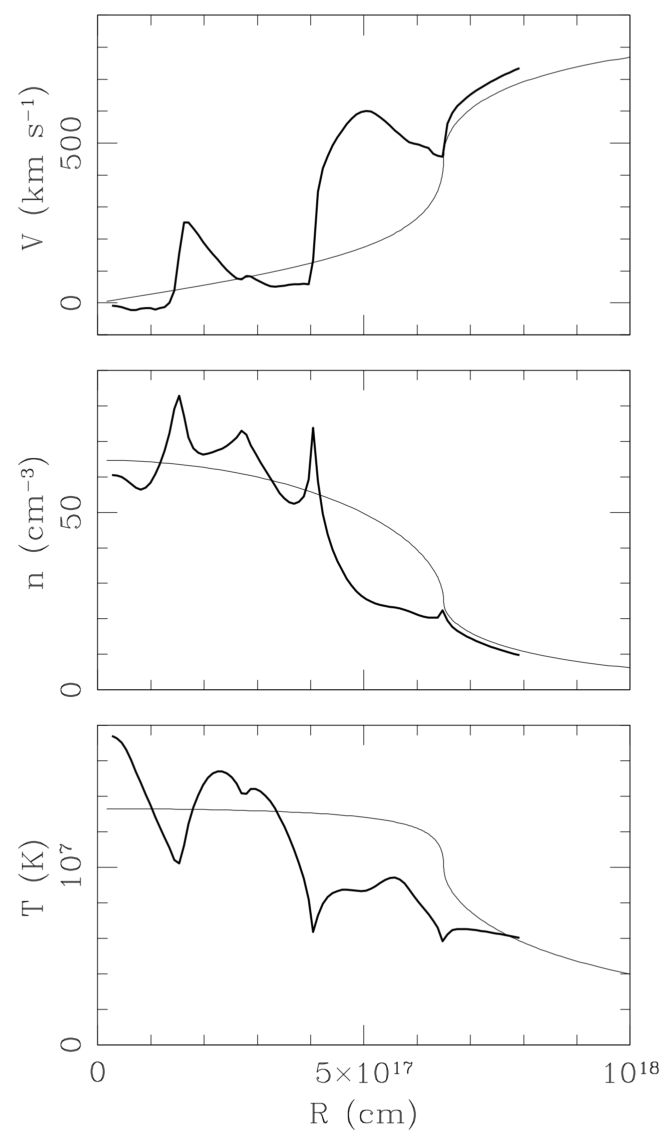

FIG. 3.—Mean flow velocity (*top*), number density of atoms and ions (*middle*), and temperature (*bottom*) as a function of spherical radius *R*. The thin lines correspond to the analytic solution (see § 2), and the thick lines correspond to the values obtained by carrying out angular averages of the flow computed in the numerical simulation (see § 3).

$V_{w,i}$ are the mass-loss rates and wind velocities of the individual stars listed in Table 1).

The remaining parameter that has to be determined in order to compute the analytic solution is the outer radius R_c of the cluster. This outer radius is not very well defined in our simulation, as it has only a relatively small number of stars. One can in principle say only that R_c has to have the same order of magnitude as the distance from the center of the cluster to the outermost star. From this, we conclude that $R_c \sim 6.5 \times 10^{17}$ cm (see Table 1) and choose this numerical value for R_c (and the $\dot{M} = 2.04 \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$ and $V_w = 919\ \mathrm{km\ s^{-1}}$ values deduced above) in order to carry out the comparison between the analytic solution and the numerical simulation.

The resulting analytic flow solution obtained from equations (12) and (15) for the asymptotically supersonic case is shown in Figure 3. This powerful cluster wind is expected to interact with the surrounding ISM and could be related with the remarkable arched filaments discovered by Yusef-Zadeh, Morris, & Chance (1984).

Comparing the mean flow obtained from the numerical simulation and the results from the analytic model (Fig. 3), we see that there is a reasonably good agreement. The analytic model of course does not show the detailed structure of the numerical radial stratification (which shows features associated with the positions of the individual stars of the cluster), but does reproduce in a convincing way the general radial trends of the flow velocity and density.

Interestingly, for radii larger than 6.5×10^{17} cm, the average flow variables (deduced from the numerical simulation) agree very well with the analytic model (see Fig. 3). This is not surprising, as one would expect that the inhomogeneities introduced by the discrete stellar wind sources are not as important outside the outer radius of the cluster.

Given the fact that we are comparing a numerical simulation of a cluster with 30 stars (see above and Table 1) with an analytic model in which a continuous, uniform distribution of stellar wind sources is assumed, the agreement obtained between these two approaches is surprisingly good. The relatively good agreement obtained between the numerical and analytic mean flow stratifications (Fig. 3) indicates that the continuous wind source distribution approach used for the analytic model (§ 2) is appropriate even for stellar clusters of only ~ 100 stars and should be quite accurate for clusters with larger numbers of stars.

4. RADIATIVE PROPERTIES

In §§ 2 and 3, we have discussed analytic and numerical models for a wind from a dense stellar cluster. For both of these models, we have assumed that the flow is not radiative. The justification for this assumption is as follows.

Let us first consider the exit time t_e that a flow parcel at an initial radius R_i takes to reach the edge R_c of the cluster,

$$t_e = \int_{R_i}^{R_c} \frac{dR}{V} = \frac{R_c}{V_w} \int_{r_i}^{1} \frac{dr}{v} , \tag{35}$$

where $r_i \equiv R_i/R_c$.

Since inside the cluster $v \ll 1$ (the maximum value is equal to $\frac{1}{2}$ for $\gamma = 5/3$, obtained at the outer boundary of the cluster), we can approximate equation (12) by

$$v \approx Ar , \tag{36}$$

which can be combined with equation (33) to give

$$t_e \approx \frac{R_c}{v_w} \frac{1}{A} \ln(1/r_i) . \tag{37}$$

In order to see whether the flow is indeed adiabatic, one has to compare the exit time with the cooling timescale

$$t_c \approx \frac{kT}{n\Lambda} , \tag{38}$$

with $\Lambda \approx 2 \times 10^{-23}\ \mathrm{ergs\ cm^3\ s^{-1}}$ for T in the 10^6–10^8 K range (see Dalgarno & McCray 1972). As both the density and the temperature depend only weakly on the spherical radius (see Fig. 3), in order to estimate the cooling timescale we can take the central values for the temperature and number density (eqs. [33] and [34]), setting $n \approx n_0$ and $T \approx T_0$ in equation (38).

In the model described in the previous section, we have $n_0 \approx 70\ \mathrm{cm^{-3}}$, $T_0 \approx 1.5 \times 10^7$ K (see Fig. 3), $V_w = 919$ km s^{-1}, and $R_c = 6.5 \times 10^{17}$ cm (see § 3). For these parameters, we obtain a cooling timescale $t_c \approx 4.7 \times 10^4$ yr, and from equation (37) we obtain an exit time

$$\left(\frac{t_e}{\mathrm{yr}}\right) \approx 1.2 \times 10^3 \ln(1/r_i) . \tag{39}$$

We then conclude that only the material with initial radii $r_i = R_i/R_c \le e^{-40}$ cools radiatively before exiting the cluster. Needless to say, this is a very small fraction of the interstellar gas within the cluster, the rest of the gas being adiabatic. In this way, we have shown that for the parameters chosen in § 3, the "cluster wind" flow is indeed adiabatic.

Therefore, we conclude that for a cluster with parameters similar to the ones deduced for the Arches cluster (see Serabyn et al. 1998), the "cluster wind" resulting from the stellar wind interaction is adiabatic and has temperatures of $\sim 1.5 \times 10^7$ K, as computed both analytically and numerically in §§ 2 and 3. This hot gas is most likely to be detected in the X-ray energy range as a diffuse component, in addition to any compact emission that could be associated with the stars.

Correcting for the fact that the Arches cluster has stars about 3 times more massive than our model, we obtain as parameters for the wind $n_0 \approx 210\ \mathrm{cm^{-3}}$, $T_0 \approx 1.5 \times 10^7$ K, and $R_c = 6.5 \times 10^{17}$ cm.

From these parameters we find that a luminosity of $\approx 6 \times 10^{35}\ \mathrm{ergs\ s^{-1}}$ will be produced as free-free radiation in the X-ray band covered by the *Chandra* satellite (0.2–10 keV). Taking a distance of 8.5 kpc to the Galactic center, an X-ray absorption after Masci, Drinkwater, & Webster (1999), and the K-band extinction of $A_K \simeq 3.2$ mag (Serabyn et al. 1998), we roughly estimate an X-ray flux of $\approx 1.8 \times 10^{-13}\ \mathrm{ergs\ cm^{-2}\ s^{-1}}$ at the Earth. This flux is detectable well above 10 σ for a 10^5 s integration with the *Chandra* satellite.

It is also of interest to estimate the expected X-ray flux of the O stars that form the Arches cluster. From a *ROSAT* survey of 42 O-type stars, Kudritski et al. (1996) find $L_X/L_{\mathrm{Bol}} \simeq -6.7 \pm 0.35$. Assuming that the O stars in the cluster have $L_{\mathrm{Bol}} \simeq 10^6\ L_\odot$, we expect fluxes from a given star about 0.001 times smaller than that of the hot cluster wind. However, all massive stars in the cluster, taken together, will contribute with a significant amount of X-ray radiation, about 0.1 that of the diffuse component.

In contrast with the X-ray situation, where the diffuse emission is expected to dominate over the compact emission from the stars, at centimeter radio wavelengths it can be shown that it is the compact free-free emission from the individual stellar winds that is more important. Again, assuming for the wind of the Arches cluster the parameters given above, a flux density of order 3 μJy is predicted for the centimeter wavelengths. This flux density is well below the sensitivity available at present. However, the free-free emission from the ionized winds of the most massive members of the cluster is expected to be detected at the level of 0.1–1 mJy, as indeed has been done recently by Lang, Goss, & Rodríguez (2000). Nonthermal radio emission has been detected from the interacting winds of a few massive binary systems (Becker & White 1985; Williams et al. 1997; Contreras et al. 1997). Nevertheless, in all known cases the separation between the stars is smaller than 0.01 pc, a much shorter distance than the typical value of 0.1 pc that separates the massive members of the Arches cluster. We conclude that a significant nonthermal component between stars is not expected, again in agreement with the observations of Lang et al. (2000).

It might also be possible to detect part of the gas within the cluster which could be in a higher density, photoionized phase (with temperatures of $\sim 10^4$ K). For example, lower mass young stars present in the cluster could have lower velocity winds which would go through radiative shocks. The postwind shock material of these stars would be photoionized by the O stars of the cluster, producing a continuum and emission-line spectrum of an H II region.

It is also possible that part of the high-density, molecular material from which the stellar cluster was formed is still present as a dense, photoionized component which has not yet been flushed out of the cluster by the interaction with the stellar winds. This component would also contribute an H II region spectrum to the emission from the interstellar material within the cluster.

In order to study these possibilities numerically, it will be necessary to carry out very high numerical resolution simulations, since the dense photoionized material will be confined to narrow sheets. Such simulations are beyond our current computational capacity.

5. CONCLUSIONS

We have developed an analytic, "mass-loaded wind" analytic model for the "cluster wind" flow resulting from the stellar wind interaction in a dense cluster of massive stars. Depending on the properties of the surrounding ISM, one can have either fully subsonic solutions (for the case of a high-pressure environment) or asymptotically supersonic solutions. The latter type of solution is more likely to be applicable to the case of real stellar clusters, unless they happen to be embedded in a particularly dense region of the ISM.

We have also computed a three-dimensional numerical simulation of the multiple wind interaction in a stellar cluster composed of 30 stars (the actual simulation having been done only for an octant with five stars). From the final, steady configuration reached by the flow, we have computed angular averages to obtain a mean flow as a function of distance from the center of the cluster. We find that this mean flow agrees very well with the analytic, mass-loaded wind solution.

For the parameters of the Arches cluster (see Serabyn et al. 1998), the cluster wind is adiabatic and has temperatures of $\approx 1.5 \times 10^7$ K. This wind is most likely to be detected in the X-ray energy range. In particular, we suggest that the X-ray emission from this intracluster gas in the "Arches" cluster could be detected with the *Chandra* satellite.

In contrast, in the radio centimeter wavelengths, it is the free-free emission from the winds of the individual stars that should be dominant, a result in agreement with the observations of Lang et al. (2000).

We speculate that there could be a cool, high-density photoionized component (corresponding either to material of the cloud from which the cluster was formed or to material injected by winds from young, low-mass stars present in the cluster) mixed in with the coronal gas of the cluster wind. If present, this material could be detected as emission of radio continuum or of collisionally excited or recombination lines in the infrared wavelength range.

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