Steady models of radiatively modified conductively driven evaporation from interstellar clouds

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Summary. The non-equilibrium ionization structures and radiative loss rates in and the dynamical structures of conductive interfaces between spherical interstellar clouds and the hot gas in which they are embedded were calculated self-consistently. The plasmas were assumed to be unmagnetized and only subsonic evaporation was studied. Mass loss rates and the column densities of several observable ions were calculated for interfaces between clouds having a range of radii and being embedded in media with temperatures of $5 \times 10^5$ and $10^6$ K. The column densities of $O^{++}$, $N^{++}$, and $C^{++}$ in the interfaces are in general compatible with existing ultraviolet absorption data, but the model linewidths may be larger than those observed. If the extreme ultraviolet background emission originates in conductive interfaces around nearby clouds, the pressure of the local interstellar medium must be about $10^{-11}$ erg cm$^{-3}$; the high pressure conductive interfaces do not produce the observed far ultraviolet emission lines.

1 Introduction

Cooling in evaporating material at hot gas-cloud interfaces may dominate the radiative losses of a supernova remnant in a cloudy medium (McKee & Ostriker 1977; Cowie, McKee & Ostriker 1981), emissions from the interface zones may contribute to the EUV and soft X-ray backgrounds (Stern & Bowyer 1979), and interstellar ultraviolet absorption features of OVI and of other moderately and highly ionized species may originate in interface zones. (Castor, McCray & Weaver 1975; McKee & Ostriker 1977; Weaver et al. 1977; Cowie, Taylor & York 1981). Considerable effort has been expanded on the study of conductively driven mass loss (Penston & Brown 1970; Graham & Langer 1973; Castor, McCray & Weaver 1975; Cowie & McKee 1977; McKee & Cowie 1977; Weaver et al. 1977; Balbus & McKee 1982; Draine & Giuliani 1984; Giuliani 1984; Balbus 1986.) Alternatively, the heating of the outer layers of clouds embedded in turbulent media may be dominated by wave dissipation (Hartquist & Morfill 1984) or cloud dispersal may be driven by pressure differences in the hot material produced by the Bernoulli effect as flow around the cloud occurs (Woodward 1976; Nittmann, Falle & Gaskell 1982; Heathcote & Brand 1983; Hartquist et al. 1986). The last possibility receives some support from
the observation of high latitude, diffuse molecular clouds, many of which have such large linewidths that they must be expanding coherently (Blitz, Magnani & Mundy 1984; Magnani, Blitz & Mundy 1985); the dispersal of such clouds is not driven by processes which operate only in thin boundary layers at the cloud surfaces.

However, a major advantage in studying conduction fronts is the relative ease with which their structures can be calculated if the clouds are spherical and flow is assumed to be purely radial. Further, while other processes may determine the gross structures and rates of mass loss, dissipation of the small-scale structures, which eventually must form during any type of mass loss, must be by conduction.

Radiative cooling can suppress the conductively driven mass loss rate. Previous work on conduction fronts includes calculations of static equilibrium structures in which radiative losses balance conductive heating. In a dynamic interface zone, the heating time-scale is often shorter than the ionization time-scale and the non-equilibrium ionization structure and cooling must be computed when calculating the dynamical structure. We describe a model of interstellar cloud – hot intercloud medium conductively dominated interfaces for which the simultaneous solutions of the steady hydrodynamic equations and equations governing the non-equilibrium ionization structure and cooling have been obtained.

Section 2 gives a description of the numerical model. In Section 3 the results for the flow structure and ionization structure are discussed for conductive interfaces in which the pressure is about 5000 K cm$^{-3}$ x $k$ (where $k$ is the Boltzmann constant) and the asymptotic temperature is either $10^6$ K or $5 \times 10^6$ K. The models were constructed for a range of different cloud radii but were restricted to interface structures in which the flows are subsonic. The mass loss rates and the column densities of some ions like C$^+$, N$^+$ and O$^{2+}$, for these models are given and the effective cooling rate of an inhomogeneous interstellar medium containing evaporating clouds is calculated. In Section 4 results for emission spectra of interfaces are presented; results for high pressure models are included. In Section 5 these results are compared to the observations of EUV- and soft X-ray background radiation, of ultraviolet- O vi, N v, C iv, Si iv, S iv, and Si vi absorption lines, and of some far-ultraviolet emission lines which are believed to be of interstellar origin. We consider whether these observed features could originate in cloud-hot interstellar medium conductive interfaces.

2 The model

We, like many other authors, assume the medium to contain no magnetic field and the motion from the spherical cloud to be purely radial. In reality, a cloud embedded in a supernova remnant will be surrounded by a moving hot gas which wraps the field lines around the cloud; the angle of the field relative to the normal of the cloud surface will approach $\pi/2$ over most of the cloud surface if the flow relative to the cloud is very supersonic and very super Alfvénic. In cases of subsonic flows, the presence of the field may decrease the conductively driven mass loss rate only by a factor of a few relative to that in the field free case.

Further, we assume the flow to be steady. One necessary condition for a flow in the interface region to be steady requires the flow time through the interface region to be short relative to the time for the cloud to evaporate. Another necessary condition is that the time-scale for fluctuations in the external medium be long compared to the flow time through the interface; the condition does not obtain in interfaces in which radiative losses suppress the conductively driven mass loss velocity to a very low value. Together these two necessary conditions are insufficient to ensure that the flow through the interface is steady as some conductive interfaces may be thermally unstable.
Our assumptions imply that

$$4\pi G r^2 = \dot{M}$$

(1)

throughout an interface where $\dot{M}$ is constant, $\rho$ is the mass density, $v$ is the radial velocity, and $r$ is the distance from the cloud centre. The equation of motion is

$$\frac{\dot{M}}{4\pi r^2} \frac{dv}{dr} = -\frac{d}{dr} \left( \frac{\rho k T}{\mu} \right)$$

(2)

where $T$ is the temperature, $\mu$ is the mean mass per particle in atomic mass units, and $k$ is Boltzmann's constant. The fluid equation for the energy content of the gas is

$$\frac{\dot{M}}{4\pi r^2} \left[ \frac{d}{dr} \left( \frac{1}{2} v^2 \right) + \frac{5k}{2\mu} \frac{dT}{dr} + \frac{5kT}{2\mu(1+\eta)} \frac{d\eta}{dr} \right] - \frac{1}{r^2} \frac{d}{dr} \left( r^2 K \frac{dT}{dr} \right) + \Lambda n e - \Gamma n + Q_i = 0.$$  

(3)

$n$ and $n_e$, $K$, $\Lambda$, $\Gamma$ and $Q_i$ are the number densities of nuclei and free electrons, the coefficient of conductivity, the radiative cooling rate coefficient, the heating rate per nucleon due to non-conductive sources (e.g. photoionization of grains) and the rate per unit volume at which thermal energy is consumed to ionize the gas. $\eta = n_e/n$ is the fractional ionization.

We discuss the calculation of $\Lambda$ and the value taken for $\Gamma$ below. If $\gamma_i(M)$ is the total collisional ionization rate of species $M$ having an ionization potential of $I_M$, then

$$Q_i = \sum M \gamma_i(M)n(M)I_M$$

(4)

where the sum is over all species and $n(M)$ is the number density of $M$.

We rewrite the fluid equations

$$\phi \equiv \frac{dT}{dr}$$

(5)

$$(1-M_i) \frac{dv}{dr} = \frac{v \phi}{T} - \frac{2v}{r} - \frac{v}{(1+\eta)} \frac{d\eta}{dr}$$

(6)

with

$$M_i = \frac{\mu v^2}{kT},$$

(7)

$$K \frac{d\phi}{dr} = \frac{\dot{M}}{4\pi r^2} v \frac{dv}{dr} + \frac{5\dot{M}}{8\pi r^2} \frac{k}{\mu} \phi \left( \frac{dK}{dT} + \frac{dK}{d\eta} \frac{d\eta}{dr} \right)$$

$$- \frac{2K}{r} \phi + (\Lambda n e - \Gamma n) + \left( Q_i + \frac{\dot{M}}{4\pi r^2} \frac{5kT}{2\mu(1+\eta)} \frac{d\eta}{dr} \right).$$

(8)

Each of the six terms into which we have divided the expression on the right-hand side of equation (8) is associated with a physically different process. They respectively represent rates of energy density change corresponding to changes in the kinetic energy flux, and in the enthalpy flux, and in the coefficient of conductivity, resulting from the radial convergence of the conductive heat flux, arising from radiative cooling and heating, and caused by energy absorbed in ionizing the gas. In low Mach number flows the first and last terms are never important but were included in the model calculations.
For the heat conduction coefficient we take

$$K = K_0 = 7 \times 10^{-11} T^{1/2} \left( \frac{1}{8.7 \times 10^3 T^2} + \frac{n(H)}{n_e \sigma_H} \right)^{-1} + 2.5 \times 10^3 T^{1/2}$$  \hspace{1cm} (9)$$

where $\sigma_H$ is the collision cross-section for electrons with H atoms.

The first term on the right-hand side is due to conduction by electrons where scattering by electrons (Spitzer 1962) and scattering by neutral H atoms are considered. The collision cross-section, $\sigma_H$, is in the range of $1-3 \times 10^{-15}$ cm$^2$ in the relevant temperature range from $10^4-10^5$ K (cf. Massey & Burbh 1969; Nakano & Umebayashi 1986). The second term is due to conduction by hydrogen (Parker 1953) where scattering of H on H$^+$ has been neglected because electron conductivity will dominate when the fractional ionization is sufficiently large for H$^+$--H scattering to determine the mean free path of the H atoms. In some of our calculations we have followed Balbus & McKee (1982) in setting

$$K = K_0 = \frac{1.03 \times 10^{-17} n_e T^4}{1.72 \times 10^{-11} n_e T^{3/2} + 6 \times 10^{-7} T^{5/2} (dT/dr)} + 2.5 \times 10^3 T^{1/2}$$  \hspace{1cm} (10)$$

when saturation effects are important; in others we have used $K = K_0$ throughout. In all cases we found $K_0/K_0 < 2$.

The calculation of $\Lambda$, $d\eta/dr$, and $Q$, required that the non-equilibrium ionization structure of the gas be followed. The cosmic abundances of the elements considered in the calculations are taken from Anders & Ebihara (1982). Especially for the calculations of the emission spectra the depletion of some of the heavier elements has to be taken into account as will be discussed in Section 4.

The ionization rate coefficients and many of the recombination rate coefficients were taken from the compilation made by Arnaud & Rothenflug (1985); recombination rates not given by them were extracted from the paper by Shull & van Steenburg (1982). The recombination rate coefficient of He$^{2+}$ was an exception and was taken from Aldrovandi & Piquinot (1973). The charge transfer processes listed by Arnaud & Rothenflug were included. Electron impact induced emissions in 208 lines found to dominate the cooling of equilibrium plasmas (Gaetz & Salpeter 1983) and from an additional 110 lines which lie in the wavelength range of 2–300 Å and which were selected from the compilation of Kato (1976) because of the large collision strengths associated with them and the large abundances of the ions from which they arise, were included in the calculation of $\Lambda$ and the spectrum. The contribution of the continuum emission to the cooling rate is always less than 10 per cent and was not included in the determination of $\Lambda$ though continuum processes were taken into account in the calculation of the spectrum; formulae from Gronenschild & Mewe (1978) were used for the computation of the spectral contributions from recombination, free–free, and two photon emissions.

For each model the fluid equations and the equations governing the ionization structure were integrated outwards from the cloud boundary at the radius $R_0$. The temperature of the cloud edge was specified to be $T_0 = 8 \times 10^3$ K in all cases in accord with the concept of photoionized cloud edges. The other boundary conditions at $R_0$ on the density, $n_0$, and the mass loss rate, $\dot{M}$, were varied in search of solutions which asymptotically approach the specified values $T_\infty$ and $n_\infty$ at infinitely great distance from the cloud. The boundary condition for the velocity is then determined by the choice of $n_0$ and $\dot{M}$. We chose a constant hydrogen ionization rate due to non-collisional processes to maintain a 10 per cent hydrogen fractional ionization at $r = R_0$ and took very high non-collisional ionization rates for all species with ionization potentials less than that of atomic hydrogen to ensure that such species are nearly fully ionized; procedure specified $\eta = \eta_0$ at $R_0$. We can approximate $\eta = \eta_\infty$ at large $r$ by assuming that hydrogen, helium, and
carbon are ionized fully and that oxygen is six times ionized. Because we considered low Mach number flows, we made an initial guess for \( n_0 \) by assuming constant pressure through the flow region, but iteration was necessary. \( \dot{M} \) is the parameter to which the resultant \( T_e \) is most sensitive. The volume heating rate due to grain photoionization is proportional to \( n \) over a wide temperature range. We have not tried to calculate \( \Gamma \) using a specific grain model. Rather we assumed that the non-conductive, non-hydrodynamic heating term is proportional to \( n \) as appropriate for grain photoionization and chose the absolute value such that heating balances the radiative losses at the cloud boundary (\( \Gamma = \Lambda n \) at \( R_0 \)). The calculations show that the heating term is never important in the models except for large distances from the cloud. At large \( r \) the dissipation of supernova remnant energy maintains the temperature of the gas in a manner which is not understood well enough to allow us to describe the behaviour of \( \Gamma \) at large \( r \). There is no certainty. In our models we have set \( \Gamma = \Lambda n \) for all \( T \geq T_c \) where \( T_c \) is a temperature close to \( T_e \) which we specified. \( T_c \) was usually in the range \( 0.9 \leq T_c \leq 0.99 \) \( T_e \). The structures of models for which \( R_0 \) is relatively small but large enough that the flow is never supersonic are insensitive to our choice of \( T_c \), but the structures of models in which \( R_0 \) is large and radiative cooling is more important are sensitive to our choice of \( T_c \).

3 Results

If the cloud is small enough or the external temperature is high enough but the flow is still subsonic everywhere, equation (3) often is approximated well by

\[
\frac{\dot{M}}{4\pi r^2} \left\{ \frac{5k}{2\mu} \frac{dT}{dr} - \frac{1}{r^2} \frac{d}{dr} \left[ r^2 K \frac{dT}{dr} \right] \right\}
\]

(11)

which, if \( \mu \) is constant, can be solved analytically; for the mass loss rate one finds (Cowie & McKee 1977)

\[
\dot{M} = 2.75 \times 10^{10} \left( \frac{T_e}{10^6 \text{ K}} \right)^{0.52} (R_0/\text{pc}) \text{ g s}^{-1}.
\]

(12)

To demonstrate that equations (11) and (12) are good approximations in some realistic cases we considered the evaporation of a cloud with \( R_0 = 1 \times 10^{19} \text{ cm} \) and \( T_0 = 8 \times 10^3 \text{ K} \) into a medium with \( T_e = 10^6 \text{ K} \) and \( n_e (1 + \eta_e) T_e = 5 \times 10^2 \text{ cm}^{-3} \text{ K} \).

Fig. 1 shows the computed model and approximate but analytically derived temperature profiles for this case; it also shows the computed model profiles for velocity, pressure, and fractional ionization. For \( T \approx 2 \times 10^5 \text{ K} \) agreement between the two temperature profiles is excellent. This agreement is achieved for different values of \( \dot{M} \), however, which are \( 8.9 \times 10^{19} \text{ g s}^{-1} \) in the analytic approximation and \( 6.2 \times 10^{17} \text{ g s}^{-1} \) for the numerical model. The discrepancy between the two temperature profiles at lower temperatures can be understood by noting that \( T_c = 0 \) for the analytic solution and by studying Fig. 2 in which the dominant terms (the second, third, fourth and fifth terms) on the right-hand side of equation (8) are shown as functions of the radius; at a radius of about \( r = 1.01 R_0 \) in this model the fifth term, which is due to radiative cooling and heat absorption from external sources, is dominant and is responsible for the strong steepening of the temperature gradient.

Much of the cooling in the lower temperature region is due to the electron impact induced emission of atomic hydrogen which remains abundant to much higher temperatures than it would if the ionization structure attained equilibrium. The results represented in Fig. 3 allow one to compare the deviations of other ion abundances from those attained in equilibrium plasmas for the same model calculations as represented by Fig. 1. For the calculation of the equilibrium abundances of the ions we used the same data base for the atomic collision processes as for the interface models.
Figure 1. The structure of an interface zone. The cloud radius, $R_0$, the temperature, $T_0$, and the external temperature $T_e$, and pressure, $P_e$, were taken to be $10^9 \text{ cm}$, $8000 \text{ K}$, $10^8 \text{ K}$, and $6.9 \times 10^{-13} \text{ erg cm}^{-3}$. The profiles for temperature, $T$, the flow velocity, $v$, the gas pressure, $P$, and the fractional ionization, $\eta$, are shown (the vertical scale for $\eta$ extends from 0 to 2). Curve a gives the temperature profile obtained by solving equation (11) analytically.

Figure 2. The importance of different terms in the energy equation. The curves give the values of (2) the second, (3) the third, (4) the fourth, and (5) the fifth term on the right-hand side of equation (8) as a function of the radius. The results are for the same model as the one for which the profiles in Fig. 1 are shown. Radiative cooling is dominant at a radius around $r=1.01 R_0$ where it is responsible for a further steepening of the temperature profile.
Mass loss rates were derived from model calculations for different cloud radii and temperatures of the hot interstellar medium of $5 \times 10^5$ and $10^6$ K. Figs 4 and 5 show how the calculated mass loss rate varies with cloud radius when the cloud temperature is taken to be $8000$ K and the pressure of the external medium is $6.9 \times 10^{13}$ erg cm$^{-3}$. For smaller clouds and higher temperatures of the surrounding medium one finds agreement between the approximate calculation of the mass loss rate by equation (12) and the numerical calculation within a factor of 2–3. However, the approximate result for the mass loss rate is not in good agreement for larger clouds embedded in lower temperature media. The larger deviations occur for clouds around which the radiative losses become more important over a large region than the enthalpy flux in balancing the conductive heat loss. When radiative losses become too important at temperatures near $T_\infty$, $\dot{M}$ depends sensitively on $T_\infty$, the temperature above which $\Gamma$ is taken to be equal to $\Lambda_\infty$, and we are unable to derive an unambiguous value for $\dot{M}$; in Figs 4 and 5 the curves are truncated at the cloud radii above which $\dot{M}$ depends sensitively on the assumed details of the way in which the dissipation of supernova remnant energy maintains the temperature at large $r$. The radii of clouds for which $\dot{M}$ is given in Figs 4 and 5 are bound from below because in a series of models with a fixed requirement for $T_\infty$ and decreasing cloud radii the maximum Mach number of the flow increases till the solution becomes supersonic at a critical cloud radius. We have terminated the calculations short above this critical radius. The mass loss rates, maximum evaporation speeds and maximum Mach numbers of the flow are tabulated for various models in Table 1.

Ultraviolet absorption features of O VI, N V, and C IV observed in the spectra of hot stars within a distance of a few kpc from the Sun (e.g. Jenkins & Meloy 1974; York 1977; Jenkins 1978a, b; Morton & Bhavsar 1979; Smith & Hartquist 1980; Cowie, Taylor & York 1981; Gry, York & Vidal-Madjar 1985) may originate in interface zones (Castor, McCray & Weaver 1975; McKee & Ostriker 1977; Weaver et al. 1977; Cowie et al. 1981). Table 2 contains the model column densities of O II, N II, C II, Si II, S II, and S III in the interface zones. The integrations extended from the cloud edge to $r$ equal to 10 times the cloud radius; the temperatures at which the integrations were
Figure 4. The rate of mass loss into a $10^6$ K medium for clouds with different radii. The cloud temperature and the pressure of the external medium were taken to be 8000 K and $6.9 \times 10^{-13}$ erg cm$^{-3}$. Curve (a) gives the model mass loss rates obtained when expression (9) is used for the coefficient of conductivity, while curve (b) gives the mass loss rates obtained when expression (10) is used. Curve (c) is calculated from equation (12) which gives an analytically derived approximation for $M$. The curves are truncated at radii above which the mass loss rate is very sensitive to the assumed behaviour of $\Gamma$ at high temperatures.

Figure 5. The rate of mass loss into a $5 \times 10^5$ K medium for clouds with different radii. The results represented in this figure are analogous to those given in Fig. 4 but are for a lower temperature of the external medium.
Table 1. The mass loss rates and maximum evaporation speeds for various models.

<table>
<thead>
<tr>
<th>Model</th>
<th>$T_\infty$ (K)</th>
<th>$\kappa$</th>
<th>$R_0$ (cm)</th>
<th>$n_0$ (cm$^{-3}$)</th>
<th>$\dot{M}$ (g/s)</th>
<th>$v_{\text{max}}$ (cm/s)</th>
<th>$M_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.6a)</td>
<td>mod.</td>
<td>3(18)</td>
<td>0.74</td>
<td>7.5(18)</td>
<td>9.6(6)</td>
<td>0.7</td>
</tr>
<tr>
<td>B</td>
<td>&quot;</td>
<td>mod.</td>
<td>3(18)</td>
<td>0.66</td>
<td>1.5(19)</td>
<td>3.0(6)</td>
<td>0.4</td>
</tr>
<tr>
<td>C</td>
<td>&quot;</td>
<td>class.</td>
<td>1(19)</td>
<td>0.69</td>
<td>6.2(19)</td>
<td>3.8(6)</td>
<td>0.5</td>
</tr>
<tr>
<td>D</td>
<td>&quot;</td>
<td>mod.</td>
<td>1(19)</td>
<td>0.60</td>
<td>3.5(19)</td>
<td>2.0(6)</td>
<td>0.3</td>
</tr>
<tr>
<td>E</td>
<td>&quot;</td>
<td>class.</td>
<td>2(19)</td>
<td>0.60</td>
<td>1.1(20)</td>
<td>1.6(6)</td>
<td>0.2</td>
</tr>
<tr>
<td>F</td>
<td>&quot;</td>
<td>class.</td>
<td>4(19)</td>
<td>0.58</td>
<td>1.7(20)</td>
<td>6.4(5)</td>
<td>0.1</td>
</tr>
<tr>
<td>G</td>
<td>&quot;</td>
<td>mod.</td>
<td>4(19)</td>
<td>0.57</td>
<td>1.3(20)</td>
<td>5.1(5)</td>
<td>0.08</td>
</tr>
<tr>
<td>H</td>
<td>5(5)</td>
<td>mod.</td>
<td>3(17)</td>
<td>0.73</td>
<td>1.6(17)</td>
<td>3.0(6)</td>
<td>0.7</td>
</tr>
<tr>
<td>J</td>
<td>&quot;</td>
<td>mod.</td>
<td>6(17)</td>
<td>0.64</td>
<td>3.4(17)</td>
<td>1.9(6)</td>
<td>0.4</td>
</tr>
<tr>
<td>K</td>
<td>&quot;</td>
<td>class.</td>
<td>8(17)</td>
<td>0.73</td>
<td>8.4(17)</td>
<td>3.6(5)</td>
<td>0.7</td>
</tr>
<tr>
<td>L</td>
<td>&quot;</td>
<td>mod.</td>
<td>1(18)</td>
<td>0.60</td>
<td>5.7(17)</td>
<td>1.2(6)</td>
<td>0.25</td>
</tr>
<tr>
<td>M</td>
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<td>class.</td>
<td>2(18)</td>
<td>0.59</td>
<td>1.6(18)</td>
<td>9.8(5)</td>
<td>0.2</td>
</tr>
<tr>
<td>N</td>
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<td>mod.</td>
<td>2(18)</td>
<td>0.60</td>
<td>1.1(18)</td>
<td>6.1(5)</td>
<td>0.15</td>
</tr>
<tr>
<td>O</td>
<td>&quot;</td>
<td>class.</td>
<td>4(18)</td>
<td>0.58</td>
<td>2.4(18)</td>
<td>3.9(5)</td>
<td>0.08</td>
</tr>
</tbody>
</table>

a) parenthesis enclose powers of 10

b) "mod." and "class." respectively designate the use of eqn. (10) or eqn. (9) for the calculation of $\kappa$

c) $v_{\text{max}}$ and $M_{\text{max}}$ are the maximum values for the flow speed and the Mach number in the interface zone, respectively.

truncated were roughly $4.8 \times 10^5$ and $9.6 \times 10^5$ K for the $5 \times 10^5$ and $10^6$ K models, respectively. The regions outside the truncation points do not contribute significantly to the column densities listed in Table 2. For comparison with the observations we have also listed the outflow velocity and gas temperature of the region which contributes most to the column density of O$^5^-$. For all models listed in Table 2 the gas phase heavy element abundances were taken to be undepleted. Column densities for models with element depletion will be given in Section 4.

Table 3 contains data on the total radiative losses from different model interface zones. The integrated luminosity is given by

$$L_{\text{rot}}(R_T) = 4\pi \int_{R_0}^{R_T} \lambda n n_e r^2 \, dr$$  \hspace{1cm} (13)

where $R_T$ is the radius at which the integration is terminated. Table 3 gives the values of $L_{\text{rot}}$ for $R_T = 10 \, R_0$.

With the above results one can calculate an effective cooling rate of a hot interstellar medium with embedded, evaporating clouds. If we take $L_{\text{co}}$ for the cooling power per unit volume for the hot ambient medium we find the following enhancement factor for the cooling rate in the...
Table 2. Column densities of several important ions in different model interface zones.

<table>
<thead>
<tr>
<th>model</th>
<th>$R_0$ (cm)</th>
<th>$T_0$ (K)</th>
<th>$N_{H^0}$ (cm$^{-2}$)</th>
<th>$N_{C^3+}$ (cm$^{-2}$)</th>
<th>$N_{N^4+}$ (cm$^{-2}$)</th>
<th>$N_{O^5+}$ (cm$^{-2}$)</th>
<th>$&lt;v(O^5+)&gt;$ (cm/s)</th>
<th>$T(O^5+)^c$ (K)</th>
<th>$N_{Si^3+}$ (cm$^{-2}$)</th>
<th>$N_{S^3+}$ (cm$^{-2}$)</th>
<th>$N_{S^5+}$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3(18)$^a$</td>
<td>1(6)</td>
<td>4.5(16)</td>
<td>2.5(12)</td>
<td>6.2(11)</td>
<td>7(12)</td>
<td>2(6)</td>
<td>8.0(5)</td>
<td>1.2(11)</td>
<td>3.4(10)</td>
<td>9810</td>
</tr>
<tr>
<td>C</td>
<td>1(19)</td>
<td>1(6)</td>
<td>5(16)</td>
<td>3.8(12)</td>
<td>1.2(12)</td>
<td>1.4(13)</td>
<td>2.5(6)</td>
<td>7.0(5)</td>
<td>1.4(11)</td>
<td>4(10)</td>
<td>1.8(11)</td>
</tr>
<tr>
<td>D</td>
<td>1(19)</td>
<td>1(6)</td>
<td>5(16)</td>
<td>2.7(12)</td>
<td>1.0(12)</td>
<td>1.2(13)</td>
<td>1.8(6)</td>
<td>6.7(5)</td>
<td>1.0(11)</td>
<td>3.2(10)</td>
<td>1.4(11)</td>
</tr>
<tr>
<td>F</td>
<td>4(19)</td>
<td>1(6)</td>
<td>1(17)</td>
<td>2.8(12)</td>
<td>1.1(12)</td>
<td>2.0(13)</td>
<td>5.5(5)</td>
<td>4.5(5)</td>
<td>1.2(11)</td>
<td>6.4(10)</td>
<td>1.5(11)</td>
</tr>
<tr>
<td>H</td>
<td>3(17)</td>
<td>5(5)</td>
<td>3.6(16)</td>
<td>1.3(12)</td>
<td>3.5(11)</td>
<td>3.2(12)</td>
<td>2.5(5)</td>
<td>4.7(5)</td>
<td>7.6(10)</td>
<td>2.5(10)</td>
<td>6(10)</td>
</tr>
<tr>
<td>M</td>
<td>2(18)</td>
<td>5(5)</td>
<td>6.5(16)</td>
<td>3(12)</td>
<td>8.5(11)</td>
<td>1.2(13)</td>
<td>3(5)</td>
<td>4.2(5)</td>
<td>1.4(11)</td>
<td>5(10)</td>
<td>1.4(11)</td>
</tr>
<tr>
<td>N</td>
<td>2(18)</td>
<td>5(5)</td>
<td>8(16)</td>
<td>3.2(12)</td>
<td>7.5(11)</td>
<td>1.1(13)</td>
<td>1.8(5)</td>
<td>4.1(5)</td>
<td>2.2(11)</td>
<td>8(10)</td>
<td>1.2(11)</td>
</tr>
<tr>
<td>O</td>
<td>4(18)</td>
<td>5(5)</td>
<td>1(17)</td>
<td>3(12)</td>
<td>1(12)</td>
<td>1.7(13)</td>
<td>2.5(5)</td>
<td>3.8(5)</td>
<td>1.2(11)</td>
<td>7(10)</td>
<td>1.6(11)</td>
</tr>
</tbody>
</table>

$a)$ parenthesis enclose powers of 10

$b)$ mean outflow velocity of the $O^{5+}$ ions

$c)$ mean temperature of the $O^{5+}$ ions
Table 3. Radiative energy loss of model interface zones and enhancement factors for the cooling of a cloudy medium.

<table>
<thead>
<tr>
<th>model</th>
<th>$R_o$ (cm)</th>
<th>$T_m$ (K)</th>
<th>$L_{tot}(r &lt; 10R_o)$ (^b)</th>
<th>$F_2$ (^c)</th>
<th>$F_{10}$ (^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3(18) (^a)</td>
<td>1(6)</td>
<td>7(32)</td>
<td>5.8(3)</td>
<td>7.8(3)</td>
</tr>
<tr>
<td>C</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.2(34)</td>
<td>1.5(3)</td>
<td>3.6(3)</td>
</tr>
<tr>
<td>D</td>
<td>1(19)</td>
<td>&quot;</td>
<td>1.0(34)</td>
<td>1.1(3)</td>
<td>3.0(3)</td>
</tr>
<tr>
<td>F</td>
<td>4(19)</td>
<td>&quot;</td>
<td>4.0(35)</td>
<td>1.9(2)</td>
<td>1.9(3)</td>
</tr>
<tr>
<td>H</td>
<td>3(17)</td>
<td>5(5)</td>
<td>1.1(31)</td>
<td>3.3(3)</td>
<td>4.8(3)</td>
</tr>
<tr>
<td>M</td>
<td>2(18)</td>
<td>&quot;</td>
<td>3.8(32)</td>
<td>2.5(2)</td>
<td>5.7(2)</td>
</tr>
<tr>
<td>N</td>
<td>2(18)</td>
<td>&quot;</td>
<td>3.4(32)</td>
<td>2.1(2)</td>
<td>5.0(2)</td>
</tr>
<tr>
<td>O</td>
<td>4(18)</td>
<td>&quot;</td>
<td>1.8(33)</td>
<td>81.0</td>
<td>3.3(2)</td>
</tr>
</tbody>
</table>

\(^a\) Parenthesis enclose powers of 10.

\(^b\) Total Radiative Energy Loss of the Interface Zone with $r \leq 10 R_o$.

\(^c\) Enhancement factors for the cooling of a cloudy medium as defined by eqn. (14) and (15) in the text where $F_2$ is the value for $R_T = 2 R_o$ and $F_{10}$ the value for $R_T = 10 R_o$.

The presence of evaporating clouds

$$G = \frac{L_{tot}(R_T)}{L_{tot} 4\pi R_T^2 f \left( \frac{R_T}{R_0} \right)^3}$$

(14)

where $f$ is the filling factor of the clouds. Definition (14) is meaningful only for $f \ll (R_T/R_0)^{-1}$.

Table 3 lists values for the parameter

$$F = G/f$$

(15)

for the cases of $R_T = 2 R_0$ and $R_T = 10 R_0$. The data show that for the smaller clouds most of the radiative losses come from the regions between $r = R_0$ and $r = 2 R_0$.

4 Extreme ultraviolet and soft X-ray background radiation

Diffuse extreme ultraviolet emission (Stern & Bowyer 1979; Paresce & Stern 1981), diffuse soft X-ray emission (cf. Burstein et al. 1977; McCammon et al. 1983) and far ultraviolet emission in the lines C iv (1549 Å) and N iv (2488 Å) (Feldman, Brune & Henry 1981; Paresce, Monsignori-Fossi & Landini 1983) have been observed and are thought to be of interstellar origin. Stern & Bowyer (1979) discussed the possibility that the EUV emission originates in the interfaces between nearby clouds and hot gas. We considered this possibility and calculated for different model interfaces the radiation intensities in those energy bands for which observational data are available. Table 4 contains the definition of the energy bands as they were used in the calculations. The observational data listed were obtained by Burstein et al. (1977) and by Stern & Bowyer (1979) whose results were revised by Paresce & Stern (1981); from the earlier reference we took values of 50, 200 and 50 s \(^{-1}\) as mean observed counts in the $M$-band, $C$-band, and $B$-band.
Table 4. Intensity in different energy bands.

<table>
<thead>
<tr>
<th>Model</th>
<th>Log Intensity (phot. cm(^{-2}) s(^{-1}) ster(^{-1}) eV(^{-1}))</th>
<th>Model Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M-Band</td>
<td>C-Band</td>
</tr>
<tr>
<td>Wave-</td>
<td>14-25</td>
<td>44-83</td>
</tr>
<tr>
<td>length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>region((R))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ob-</td>
<td>-1.5</td>
<td>-0.2</td>
</tr>
<tr>
<td>served</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(^{c})</td>
<td>-4.8</td>
<td>-2.5</td>
</tr>
<tr>
<td>C</td>
<td>-4-4</td>
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<tr>
<td>1*</td>
<td>-2.5</td>
<td>-1.4</td>
</tr>
<tr>
<td>2*</td>
<td>-2.1</td>
<td>-0.7</td>
</tr>
<tr>
<td>2</td>
<td>-1.8</td>
<td>-0.3</td>
</tr>
<tr>
<td>3*</td>
<td>-3.8</td>
<td>-1.4</td>
</tr>
<tr>
<td>4*</td>
<td>-3.5</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

---

a) \(M_{\text{max}}\) is the maximum Mach number in the gas flow

b) data from Burstein et al. (1977) and Stern and Bowyer (1979)

c) * designates those models for which element depletion was taken into account
d) parenthesis enclose powers of 10
respectively, and converted these count rates to intensities in units of photon cm$^{-2}$ s$^{-1}$ sr$^{-1}$ eV$^{-1}$ using the cited detector area, viewing angle, and transmission curves. The intensities of radiation expected from the model interfaces, as listed in Table 4, were calculated from the integral

$$I_{band} = \frac{1}{4\pi} \int_{R_0}^{R_T} \Lambda_{band} n_e n \, dr$$

where $\Lambda_{band}$ is the local non-equilibrium emissivity in lines and continuum in the given energy band and where the truncation radius $R_T = 10 R_0$ corresponds to a temperature of about $T = 0.96 T_e$.

The emissions in some energy bands are sensitive to the actual abundance of elements in the gas phase. Effects due to the possible high depletion of Fe may be expected to be particularly important. From a recent data compilation by Jenkins (1986) we adopted in some models depletion factors of roughly 2, 2, 4, 30 and 80 for the elements C, O, Mg, Si and Fe, respectively. N and S have been found to be hardly depleted, and we have assumed them to be undepleted. For comparison, Table 4 gives results for models with depleted and models with undepleted gas phase element abundances.

Because the calculated intensities of the EUV emissions for models with an ambient pressure of $P_a = 6.9 \times 10^{-13}$ erg cm$^{-3}$ are more than two orders of magnitude less than the observed intensities and since the pressure in the local interstellar medium may be much higher than the average galactic value we also considered models for higher ambient pressure. For these high pressure models the solutions depend somewhat on the way in which $\Gamma n$ is assumed to balance radiative losses, and often the temperature structure and the emission spectrum are almost independent of the exact choice of the evaporation rate. (See the discussions of Figs 4 and 5 in the text of Section 3.) In models 1, 3 and 4 the enthalpy flux and radiation are both important in balancing the heat conduction, while in model 2 radiative losses are so dominant that the solution is practically independent of the value chosen for the $\dot{M}$. Inspection of the calculated ionization structures shows that for model 2 equilibrium is almost attained for all the major ions throughout the interface while for all of the other models deviations from equilibrium are still significant.

![Figure 6](https://example.com/image6.png)

**Figure 6.** Emission spectrum of model 4*. The EUV- and soft X-ray emission spectrum calculated for model 4* ($R_0 = 10^4$ cm, $T_e = 10^6$ K, $P_a = 1.1 \times 10^{-11}$ erg cm$^{-3}$, truncation radius, $R_T = 10^4$ cm with depletion of some heavy elements in the gas phase) is shown with a resolution of 1 Å. The major lines are designated. The strong He II 256.3 Å line is a result of the deviation from ionization equilibrium.
Table 5. Column densities of several important ions.

<table>
<thead>
<tr>
<th></th>
<th>N_{H_2} (cm^{-2})</th>
<th>N_{C}^{+} (cm^{-2})</th>
<th>N_{N_2}^{+} (cm^{-2})</th>
<th>N_{O_3}^{+} (cm^{-2})</th>
<th>v_{&lt;}(O^{5+}, a) (cm^{-2})</th>
<th>T(O^{5+}, b) (K)</th>
<th>N_{Si_3}^{+} (cm^{-2})</th>
<th>N_{S_3}^{+} (cm^{-2})</th>
<th>N_{S_5}^{+} (cm^{-2})</th>
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<tr>
<td>C</td>
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<td>1.2(12)</td>
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<td>4.1(10)</td>
<td>1.8(11)</td>
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<tr>
<td>2*</td>
<td>1.4(17)d</td>
<td>2.3(17)</td>
<td>1.3(12)</td>
<td>1.0(12)</td>
<td>1.0(12)</td>
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<td>2.2(17)</td>
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<td>1.0(12)</td>
<td>1.0(12)</td>
<td>5.9(9)</td>
<td>5.6(10)</td>
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<tr>
<td>3*</td>
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<td>9.2(16)</td>
<td>2.0(12)</td>
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<td>1.2(12)</td>
<td>2.6(6)</td>
<td>6.5(5)</td>
<td>4.1(10)</td>
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<td>4*</td>
<td>1.2(17)</td>
<td>1.2(17)</td>
<td>1.2(12)</td>
<td>1.2(12)</td>
<td>1.2(12)</td>
<td>1.4(6)</td>
<td>5.8(5)</td>
<td>4.2(10)</td>
<td></td>
</tr>
</tbody>
</table>

a) mean outflow velocity of the O^{5+} ions
b) mean temperature of the O^{5+} ions
c) a * designates those models for which element depletion was taken into account
d) parenthesis enclose powers of 10

Table 6. Intensities of some observed far-ultraviolet diffuse emission lines.

<table>
<thead>
<tr>
<th>Model</th>
<th>SiIV</th>
<th>OIIV</th>
<th>NIV</th>
<th>CIV</th>
<th>OII</th>
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<tr>
<td></td>
<td>1397</td>
<td>1406</td>
<td>1488</td>
<td>1349</td>
<td>1663</td>
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<table>
<thead>
<tr>
<th></th>
<th>observed</th>
<th>3.8-4.1</th>
<th>3.8-4.14</th>
<th>3.7-4.04</th>
<th>4.1-4.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>C*</td>
<td>-0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>1.8</td>
<td>0.0</td>
</tr>
<tr>
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<td>1.9</td>
<td>3.1</td>
<td>1.9</td>
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<tr>
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<td>2.3</td>
<td>2.4</td>
<td>1.9</td>
<td>3.3</td>
<td>2.1</td>
</tr>
<tr>
<td>4*</td>
<td>0.9</td>
<td>1.6</td>
<td>1.5</td>
<td>3.1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

a) data from Feldman et al. (1981)
b) a * designates those models for which element depletion was taken into account

Fig. 6 shows an example of the soft X-ray and extreme ultraviolet radiation spectrum from an interface region for model 4* (with a cloud radius of 10^{18} cm and an ambient temperature and pressure of 10^6 K and 1.1 \times 10^{-11} erg cm^{-3}, respectively). The lines are shown with a resolution of 1 Å and the major lines are designated. One signature of non-equilibrium ionization conditions in this spectrum is the very prominent He II Ly\beta line, which is much weaker when ionization equilibrium obtains.

Table 5 gives the column densities of several important ions for the models with higher ambient pressure and for model C with depleted element abundances. As can be seen by comparison with Table 2 the column densities for a specific ion always remain of the same order of magnitude range (Si^{3+} naturally has a much lower column density in the models with heavy element depletion). In the models of interfaces around smaller clouds or with lower pressures, the outflow velocity is high resulting in substantial deviations from ionization equilibrium; for certain trans-
ient ion species, the deviation from equilibrium partly compensates for a lower gas density or a smaller radial scale of the interface zone.

Table 6 lists the model values for the intensities of several strong far ultraviolet emission lines. Observed intensities of these lines, which are believed to originate in the interstellar medium (Feldman et al. 1981), are also listed. The model results are difficult to reconcile with the observational data.

5 Discussion

The most extensive observations (Jenkins 1978a, b) of interstellar ultraviolet absorption lines are for OVI. Most of the detected OVI absorption does not arise in the evacuated regions of the local bubble or superbubble (Gry et al. 1985). The OVI lines consist of features formed in individual components containing O^{5+} column densities of about 10^{13} cm^{-2}. The calculated model column densities are of this order. However, the OVI linewidhts imply that much of the absorption takes place in gas with T=10^{3.3} K; in contrast, the model O^{5+} density weighted temperature averages in the interfaces in which P=7×10^{-11} erg cm^{-3} lie in the range of 10^{5.6}-10^{5.8} K in most cases. In the higher pressure interfaces considered in Section 4, the ionization structure tends towards equilibrium and the corresponding OVI features would be substantially narrower, but it is unrealistic to expect the pressures to be so high in most gas in which OVI absorption arises. Perhaps a more detailed comparison between observed and model profiles is necessary. Alternatively, most of the interfaces may be between clouds and gas with T=10^{5.3} K, but the distinction between absorption in the interface and the remnant becomes vague; Hartquist & Morfill (1984) have argued that turbulence invoked to broaden the remnant contribution to OVI lines would produce waves which would propagate into the interfaces and broaden lines formed in them as well. While we note that the calculated column density ratios of the various ion species listed in Tables 2 and 4 are roughly comparable with the data in the observational references cited in Section 3, we conclude that conductively dominated interfaces are probably not the sites of OVI formation. We do not reject the hypothesis that interface regions are important for the absorption but feel that their structures must be modified by non-conductive processes sufficiently to allow the ionization structure in them to tend towards equilibrium. As discussed by Dyson & Hartquist (1987) the M-band emissivity of adiabatic remnants would be enhanced considerably if material in them is picked up primarily through evaporative zones in which ionization equilibrium obtains.

The C- and B-band emissions and EUV emissions must have a local origin, while the M-band emission probably has a local contribution but may also have a contribution from more distant sources. The solar neighbourhood is known to be devoid of cold and cloudy material (cf. Frisch & York 1983) and it has been suggested that this local region is formed by a supernova remnant or a hot superbubble created by supernovae and strong stellar winds (cf. models by Cox & Anderson 1982; Innes & Hartquist 1984; Arnaud & Rothenflug 1986; Dyson & Hartquist 1987). If the bubble is still expanding and has not yet reached pressure equilibrium with the surroundings, the pressure in the local interstellar medium could be considerably higher than the average galactic value. Local pressures of the order of 10^{-11} erg cm^{-3} are required if conductive interfaces contribute significantly to the soft X-ray and EUV background.

Comparing the observed and calculated intensities in the different energy bands in more detail one notes that the models do not yield enough emission in the M-band, unless T>10^6 K, but most of the M-band emission may be expected from the hot intercloud medium rather than from the conductive interfaces, in any case. One further notes that the models tend to produce relatively too little emission in the N-band and too much in the Al+C band. The excess in the Al+C band is more enhanced in the models with a larger deviation from ionization equilibrium because in these
cases the He II Ly lines are very much enhanced and totally dominate the emission in the Al+C band. The remaining discrepancies between the best fit model (models 2* and 4*) results and the emission data are up to a factor of 3 but perhaps may reflect the simplified nature of the models which were constructed. In any case, the far ultraviolet emission lines almost certainly do not originate in conductive interfaces.

The time needed to set up a steady state conduction front has also to be considered in this discussion and to be compared to the time of the local supernova remnant age. In the Cox & Anderson (1982) model with an explosion energy of $5 \times 10^{50}$ erg, for example, an age of about $10^6$ yr has been proposed for the local supernova remnant, while in the model of Innes & Hartquist (1984) with an explosion energy of $10^{52}$ erg an age of about $4 \times 10^6$ yr gives the best fit to the observational data. If we take the flow time of the gas in the interface zone from the cloud boundary to a radius equal to twice the radius of the cloud as a measure for the time to reach a steady state configuration, we find that in the high pressure environment models with $R_0 \approx 10^{18}$ cm take on the order of $\approx 10^7$ yr to reach steady state while for $R_0 \approx 10^{19}$ cm this time is more than an order of magnitude longer. Therefore the interface zones will attain a stationary structure if the local supernova remnant has an age comparable to that of the Innes & Hartquist (1984) model, which seems to be the more attractive of the two published models, because it gives a better agreement with the observational data.

References


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Steady models of evaporation from interstellar clouds
