Photoelectric Heating of the Interstellar Gas

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Summary. I have calculated the equation of state of the interstellar gas in thermal balance and in ionization equilibrium (steady state). The gas is heated and ionized by cosmic rays and by ultraviolet photons of the interstellar radiation field with \( \lambda > 912 \, \text{Å} \) and it is cooled by collisional excitation of atoms and ions in the gas. Depletion factors of the interstellar gas atoms, derived from observations with the Copernicus satellite have been adopted. The gas is heated by ultraviolet photons through the production of photo-electrons from dust grains and Carbon atoms and through photodissociation of \( \text{H}_2 \) molecules. At low gas densities the grains become positively charged so that the photoelectric heating by dust grains is strongly reduced. The equation of state of the gas has been calculated for various values of the parameters \( \zeta_0 \), the primary cosmic ray ionization rate of atomic Hydrogen and \( y \), the photoelectric emission efficiency of the dust material. I find that for several combinations of the parameters \( \zeta_0 \) and \( y \) both the intercloud gas and the cloud gas are predominantly heated by photo-electrons from dust grains. The hot intercloud gas is stabilized against thermal instability by the non-linear dependence of the heating rate on the Hydrogen density \( n \) and the temperature \( T \) of the gas, when the grains are strongly positively charged. The transition to the cool cloud phase takes place at those gas densities where the grains become neutralized by collisions with electrons in the gas. The model which best fits the observations is characterized by \( \zeta_0 = 10^{-16} \, \text{s}^{-1} \) and \( y = 0.1 \). This model is more satisfactory than previous ones because it explains the existence of a hot rarified intercloud gas and cool dense cloud gas while requiring much less cosmic rays. Furthermore the pressure of the interstellar gas is about a factor 3 larger than in previous models.

I. Introduction

The concept of a two-phase model of the interstellar gas introduced by Field et al. (1969) has significantly increased our understanding of the physics and the dynamics of the interstellar gas. In their model the gas is ionized and heated by low-energy cosmic rays. Field et al. were forced to postulate a very high flux of low-energy cosmic rays to obtain agreement with observations of the interstellar gas. Later work has cast some doubt on the tenability of this postulate. Firstly, propagation of the low-energy cosmic rays over large distances in the galactic plane is needed to account for the postulated flux of cosmic rays, in contradiction with theoretical expectation (Kulsrud and Cesarsky, 1971). Secondly, the flux postulated is about one order of magnitude greater than the upper limits derived from the observed OH and HD densities in interstellar clouds (Black and Dalgarno, 1973; O'Donnell and Watson, 1974).

Several alternative ionization and heating mechanisms have been suggested to overcome these difficulties such as soft X-rays with \( \lambda \gtrsim 10 \, \text{Å} \) (Silk and Werner, 1969) and ultraviolet photons with \( \lambda < 912 \, \text{Å} \) (Hills, 1972; Torres-Peimbert et al., 1974; Meszaros, 1974; Lyon, 1975). Models with these ionization and heating mechanisms are strongly time-dependent because the mean free path of soft X-rays and far UV-photons are quite short compared to the typical dimensions of gas complexes in the galaxy and because the lifetimes of the sources producing this radiation are of the same order of magnitude as the recombination and cooling times of the interstellar gas (cf. Gerola et al., 1974).

By far the most promising heating mechanism suggested so far, at least for heating interstellar clouds, is heating by photoelectrons from dust grains produced by photons of the interstellar radiation field between about 1200 Å and 912 Å (Watson, 1972). This heating mechanism is attractive because these photons are so abundant in interstellar space and since most of them end up being absorbed by dust grains. The relative effectiveness of the interstellar photons for heating the interstellar

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gas compared to cosmic rays can best be illustrated by a numerical example. Taking the high cosmic ray ionization rate of atomic Hydrogen $\zeta_0 = 10^{-15}$ s$^{-1}$ postulated by Field et al., the intensity of the interstellar radiation field 3 times larger than calculated by Habing (1968) and a plausible value of the photoelectric emission efficiency $\gamma = 0.1$, I find that the amount of heat deposited in the interstellar gas by photons is greatly less than by cosmic rays. In my model the interstellar gas is ionized by a steady flux of low-energy cosmic rays and the cloud gas is ionized by photons longward of 912 Å. This is not essential; models with other sources of ionization could be constructed.

The paper is organized as follows. In Sections II and III, I discuss the ionization equilibrium, the adopted abundances and the heating and the cooling of the gas. The results of the calculation and their interpretation are presented in Section IV. One of the models of Section IV is compared with the observations in Section V. Finally, I summarize the main conclusions in Section VI.

## II. Ionization Equilibrium

I assume that interstellar H and He atoms are ionized by low-energy cosmic rays while the atoms of the heavy elements C, Mg, Si, S and Fe are ionized by the interstellar radiation field longward of 912 Å. In the calculation of the ionization equilibrium of H and He I follow Spitzer and Scott (1969) who assumed that, (i) the recombination and ionization cross sections of H and He are equal, (ii) the degree of ionization of H and He is equal, and (iii) there is no secondary ionization of He. The ionization equilibrium of H is then given by the equation

$$
\zeta_0 [(1 + x_{He})(1 + \Phi) + 2x_{He}]n(H) = z_{H}(T)n(H^+)(1 + x_{He})n(e)
$$

where $\zeta_0$ is the primary ionization rate of H, $x_{He}$ is the abundance of He relative to H and $z_{H}$ is the Hydrogen recombination coefficient (to excited levels only). The factor $(1 + \Phi)$ takes account of ionization by secondary electrons (and is tabulated by Spitzer and Scott as a function of $n(e)/n(H)$), the term $2x_{He}$ takes account of ionization of H by He recombination photons.

The ionization equilibrium of the heavy elements is given by a set of equations of the form

$$
\beta_A(\chi)n(A) = z_A(T)n(A^+)n(e)
$$

where $\beta_A$ is the photoionization rate of atom A and $z_A$ is its recombination coefficient. I only consider the ionization equilibrium between atoms and singly ionized ions. In Table 1, I list the photoionization rates and the recombination coefficients adopted in this calculation.

<table>
<thead>
<tr>
<th>Atom</th>
<th>$\beta$(s$^{-1}$)</th>
<th>$\alpha$(cm$^3$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>see text</td>
<td>$1.75 \times 10^{-10}T^{-0.70}$</td>
</tr>
<tr>
<td>C</td>
<td>$1.31 \times 10^{-10}$</td>
<td>$1.40 \times 10^{-10}T^{-0.61}$</td>
</tr>
<tr>
<td>Mg</td>
<td>$4.5 \times 10^{-11}$</td>
<td>$3.7 \times 10^{-10}T^{-0.86}$</td>
</tr>
<tr>
<td>Si</td>
<td>$1.20 \times 10^{-9}$</td>
<td>$1.50 \times 10^{-10}T^{-0.60}$</td>
</tr>
<tr>
<td>S</td>
<td>$7.2 \times 10^{-10}$</td>
<td>$1.40 \times 10^{-10}T^{-0.83}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$1.17 \times 10^{-9}$</td>
<td>$1.50 \times 10^{-10}T^{-0.65}$</td>
</tr>
</tbody>
</table>

Both are taken from the work of Black (1975). Over the range of temperatures where ionization of the heavy elements contributes significantly to the electron density the recombination coefficients in Table 1 are accurate within 10%. The average energy density of the interstellar radiation field around 1000 Å has been taken $u_{\nu} = 4 \times 10^{-17} \chi$ erg cm$^{-3}$ s$^{-1}$, where $\chi = 1$ corresponds to the radiation field calculated by Habing (1968). Unless otherwise stated I will adopt $\chi = 3$ (Jura, 1974).

The adopted abundances of the heavy elements affect the electron density and the cooling rate in the gas. There is observational evidence that most heavy elements are depleted in the interstellar gas, both in clouds and in the intercloud gas. In Table 2 I have listed the solar abundances of the heavy elements included in the calculation, the abundances observed in the interstellar clouds towards the reddened star ζ Oph (Morton, 1974) and the abundances observed in the intercloud gas towards the virtually unreddened star ζ Sco (York, 1975). In the last column I give the heavy element abundances adopted in this paper, both for the clouds and for the intercloud gas.

<table>
<thead>
<tr>
<th>Atom</th>
<th>Solar</th>
<th>ζ Oph</th>
<th>ζ Sco</th>
<th>Adopted</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>$1.0 \times 10^{-1}$</td>
<td>$1.0 \times 10^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>$3.7 \times 10^{-4}$</td>
<td>$7.4 \times 10^{-5}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>N</td>
<td>$1.15 \times 10^{-4}$</td>
<td>$2.2 \times 10^{-5}$</td>
<td>$2.9 \times 10^{-5}$</td>
<td>$2.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>O</td>
<td>$6.8 \times 10^{-4}$</td>
<td>$1.8 \times 10^{-4}$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$1.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Mg</td>
<td>$3.5 \times 10^{-5}$</td>
<td>$1.1 \times 10^{-6}$</td>
<td>$7.0 \times 10^{-6}$</td>
<td>$2.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>Si</td>
<td>$3.6 \times 10^{-5}$</td>
<td>$8.1 \times 10^{-7}$</td>
<td>$2.8 \times 10^{-6}$</td>
<td>$1.3 \times 10^{-6}$</td>
</tr>
<tr>
<td>S</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$8.3 \times 10^{-6}$</td>
<td>$1.3 \times 10^{-5}$</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$2.5 \times 10^{-5}$</td>
<td>$2.7 \times 10^{-5}$</td>
<td>$1.3 \times 10^{-5}$</td>
<td>$5.8 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

III. Heat Balance

I assume that the interstellar gas is predominantly heated by ultraviolet photons longward of 912 Å and by cosmic rays. Radiation energy is converted into heat through photoionization of electrons by Carbon atoms and by dust grains and by photodissociation of hydrogen molecules. Cosmic ray energy is converted into heat through electron emission upon ionization of Hydrogen and Helium atoms.
The interstellar gas is cooled by electronic excitation of H, N and O atoms and of C\(^{+}\), Si\(^{+}\), S\(^{+}\) and Fe\(^{+}\) ions. All cooling rates are taken from the review of Dalgarno and McCray (1972). I have included the cooling due to fine structure excitation of the electronic ground states of C\(^{+}\), O, Si\(^{+}\) and Fe\(^{+}\) by electrons and H atoms, the cooling due to metastable electronic level excitation of C\(^{+}\), N, O, Si\(^{+}\) and Fe\(^{+}\) by electrons and the cooling due to Ly\(\alpha\) excitation of H by electrons. The atomic and ionic number densities in the gas follow from the solution of the ionization equilibrium discussed in the preceding section.

I discuss the individual contributions of the different processes to the heating rate in some detail below.

**Heating by Photoelectrons from Dust Grains**

Photoelectrons emitted by dust grains are a major heat source of the interstellar gas since the number of electrons ejected from dust grains by interstellar photons is at least one order of magnitude larger than the number of electrons emitted by H and He atoms due to ionization by cosmic rays. The calculation of the heating rate of the gas by this process is complicated by the fact that the electron ejection rate and the photoelectron energy depend on the charge of the dust grains, which is a function of the temperature \(T\) and the electron density \(n(e)\) in the gas. The charge of a dust grain can be found by equating the rate of photoelectron emission from a dust grain and the rate of recombination of electrons with a dust grain (cf. Spitzer, 1968)

\[
\left(\frac{\nu_e}{\nu_0}\right) = \frac{\sigma_d}{\nu_0} \left(1 + \frac{\nu_0 - \nu_d}{kT}\right) n(e) \nu_e.
\]

Here \((\sigma_d)\) is the photoabsorption cross section and \(\sigma_d\) is the geometrical cross section of the dust grains, \(\nu\) is the photoelectric emission efficiency of the dust material, and \(\nu_e = (2kT/m_e)^{1/2}\) is the root mean square velocity of the electrons. The upper integration bound \(\nu_\alpha\) is the frequency of the Lyman limit where the radiation field is cut off and the lower integration bound \(\nu_\alpha\) is the frequency corresponding to the energy barrier that photoelectrons have to overcome before they can leave the grain. The value of \(\nu_0\) incorporates the effect of the charge of the dust grains, \(\nu_0 = \nu_d + \nu_0\), where \(\nu_d\) is the photoelectric threshold energy of the bulk dust material and \(\nu_d\) is the electrostatic potential of the grains. I have assumed that the photoelectrons do not lose energy due to scattering in the grain on their way to the surface. This is a reasonable assumption because the dust grains causing the observed absorption and scattering of starlight around 1000 Å are small [about 100 Å according to Greenberg and Hong (1974)] of the same order of magnitude as the mean free path of electrons for scattering off molecules in the dust grain (Watson, 1972; Jura, 1976). In addition I have assumed that the sticking probability of electrons colliding with grains is unity. The factor \(1 + (\nu_0 - \nu_d)/kT\) takes account of the enhanced recombination when the grains are positively charged (\(\nu_\alpha > \nu_d\)). Collisions of the grains with positive ions in the gas have been neglected because they occur much less frequently than collisions with electrons (cf. Feuerbacher et al., 1973).

I want to emphasize that the net production of electrons by grains is negligible. Taking \(h\nu_d = 10\) eV (Watson, 1972; Feuerbacher and Fitton, 1972) and \(a = 100\) Å, I find that the maximum electrostatic potential that can build up on the grain is \(\nu_0 - \nu_d = 3.6\) eV corresponding to \(\nu_0/a = 20\) electrons produced per grain. In view of the very small number density of grains this implies that the number density of electrons in the gas produced by grains is negligibly small.

If I assume that \((\sigma_d)\) equals \(\sigma_d\) and that \(\nu\) is independent of frequency (see for example Feuerbacher and Fitton, 1972) the above equation reduces to the following cubic equation

\[
x^3 + (x_k - x_d\gamma) x^2 - \gamma = 0
\]

where \(x = \nu_0/\nu_\alpha\), \(x_k = kT/\nu_\alpha\), \(x_d = \nu_d/\nu_\alpha\) and

\[
\gamma = \left(\frac{km}{8}\right)^{1/2} \frac{c^2}{h^2}\frac{\nu_\alpha}{\nu_0} T^{1/2}\frac{n(e)}{n(e)} = 2.9 \times 10^{-4} \frac{S}{T^{1/2}}
\]

This equation can be solved for \(x\) from which the electrostatic potential \(\nu_0\) and the charge of the grains, \(\nu_0/a\), can be found. For \(n(e)\) very large (\(\gamma \to 0\) and \(x \to x_k - x_d\)) the dust grains are almost neutral and for \(n(e)\) very small (\(\gamma \to \infty\) and \(x \to 1\)) the dust grains attain their maximum charge \(\nu_0 = h\nu_\alpha - h\nu_d = 3.6\) eV.

The heating rate of the gas by photoelectrons from dust grains is defined by

\[
\Gamma_d = \int \left(\frac{n(\sigma_d)}{\nu_0}\right) y \nu d\nu
\]

where \((n(\sigma_d))\) is the absorption coefficient due to dust in the interstellar dust-gas mixture. With the assumption that \(\nu\) is independent of frequency this equation becomes

\[
\Gamma_d = \langle n(\sigma_d) \rangle \frac{c^2}{2h\nu_\alpha} \nu_k \left(1 - \frac{x_k}{x}\right)^2.
\]

If \(x_k\) is neglected with respect to \(x_d\) an approximate solution of the cubic equation in \(x\) can be obtained which results in

\[
\Gamma_d \approx \langle n(\sigma_d) \rangle \frac{c^2}{2h\nu_\alpha} \nu_k \left(1 - \frac{x_d}{2\nu_\alpha + x_d}\right)^2.
\]

This expression is exact in the limits \(\gamma \gg x_d/2\) and \(\gamma \ll x_d/2\) and it is accurate to within 10% for \(\gamma \approx x_d/2\).

The numerical value of \(\langle n(\sigma_d) \rangle\) is obtained from data of the extinction and scattering of starlight. Adopting \(\lambda \approx 1000\) Å an average albedo of the dust grain of 0.5 (Witt and Lillie, 1976), taking the interstellar extinction at \(\lambda \approx 1000\) Å 5 times larger than at visual wavelength (York et al., 1973) and using Bohlin's (1975) result \(N_\alpha = 5 \times 10^{21}\)
$E_{d-v}$, I find $\langle n_d \sigma_d \rangle = 1.4 \times 10^{-21}$ n cm$^{-1}$. Inserting this in the expression of the heating rate I finally obtain

$$\Gamma_d = 7.5 \times 10^{-25} \gamma \chi n \left( \frac{1 - x_d}{x_d + 2\gamma} \right)^2 \text{erg cm}^{-3} \text{s}^{-1}$$

with the asymptotic limits

$$\Gamma_d = 7.5 \times 10^{-25} \gamma \chi n \left( \frac{1 - x_d}{x_d} \right)^2 \text{erg cm}^{-3} \text{s}^{-1} \quad (\gamma \ll x_d/2)$$

and

$$\Gamma_d = 2.2 \times 10^{-18} \frac{n^2(e)n}{T_\chi y} (1 - x_d)^2 \text{erg cm}^{-3} \text{s}^{-1} \quad (\gamma \gg x_d/2).$$

The first of the latter two expressions applies to the case that the dust grains are uncharged, the second one applies to the case that the dust grains are strongly positively charged. The second one can be obtained from the first one by multiplying with a factor $(x_d/2\gamma)^2$. Thus the heating rate is strongly reduced if the grains charge up. The reduction by the quadratic factor $(x_d/2\gamma)^2$ can be physically interpreted as follows. One factor $(x_d/2\gamma)$ takes account of the reduction of the number of photons of the interstellar radiation field that can “ionize” a charged dust grain, the second factor $(x_d/2\gamma)$ is the reduction in photoelectron energy left after the electron has overcome the electrostatic potential of the charged grain.

The heating rates are extremely sensitive to the value of the photoelectric threshold of the dust material. For instance the heating rate for dust grains with $h\nu_d = 10$ eV is about one order of magnitude smaller than for grains with $h\nu_d = 5$ eV. From the work of Watson (1972) and Feuerbacher and Fitton (1972) it appears that $h\nu_d = 10$ eV is a good estimate of the threshold energy for materials like silicate and graphite. This value of $h\nu_d$ has been adopted for the calculations to be presented in the next section. According to the same authors the numerical value of the photoelectric emission efficiency $\chi$ ranges from about 0.01 for semiconductors and graphite to about 0.1 for insulators (silicate). Jura (1976) has recently suggested that for very small grains $\gamma$ may be as large as 0.67. I shall consider $\gamma$ a free parameter of the calculation. A “best value” of $\gamma$ will be derived in Section V from a comparison with observations of the interstellar gas.

### Heating by Photoelectrons from Carbon Atoms

The heating rate due to ionization of C atoms by interstellar photons is defined by

$$\Gamma_C = \beta_C n(C) \Delta E_C$$

where the ionization rate $\beta_C$ is given in Table 1 and the photoelectron energy is $\Delta E_C = 1.06$ eV for a flat spectral energy distribution of the interstellar radiation field in wavelength units. Inserting these numbers I find

$$\Gamma_C = 2.2 \times 10^{-22} \chi n(C) \text{erg cm}^{-3} \text{s}^{-1}.$$
This equation has to be solved simultaneously with the equations of ionization equilibrium discussed in Section II, because the recombination rate coefficients are functions of the temperature. Free parameters in this calculation are the total hydrogen gas density \( n \), the cosmic ray ionization rate \( \zeta_0 \) and the photoelectron emission efficiency of dust grains \( y \). Once the temperature of the gas is known the pressure follows from the relation 
\[ P = kT \sum n_i \] 
where \( \Sigma n_i \) is the sum of the atomic-, ion- and electron densities in the gas. Figures 1, 2 and 3 show the pressure-density relation (equation of state) of the interstellar gas for several values of the primary cosmic ray ionization rate \( \zeta_0 \) as a function of the photoelectron emission efficiency \( y \) of the grains.

The curves in Figures 1, 2 and 3 are similar in shape to those in previous calculations of steady-state models of the interstellar gas. There are two stable phases where the pressure increases with density and there is an intermediate thermally unstable phase where the pressure decreases with increasing density. The dense cool stable gas phase is usually identified with interstellar clouds, the rare hot stable gas phase is identified with the intercloud gas that occupies the space between the clouds. According to the steady-state picture, clouds and intercloud gas coexist in pressure equilibrium at some pressure between \( P_{\text{max}} \) and \( P_{\text{min}} \). From Figures 1, 2 and 3 it is clear that the range of densities where the gas is unstable and the range of pressures where the clouds and the intercloud gas can be in pressure equilibrium strongly depends on the parameters \( \zeta_0 \) and \( y \).

At low gas densities \( (n \approx 10^{-2} \text{ cm}^{-3}) \) the gas pressure in Figures 1, 2 and 3 is independent of \( y \) because the ionization and the heating of the gas are dominated by cosmic rays. Photoelectric heating is strongly reduced because the electron density in the gas is so low that the grains are positively charged. At high gas densities \( (n \approx 10^2 \text{ cm}^{-3}) \) the ionization and heating of the gas are dominated by the interstellar radiation field. The electron density is sufficiently high to reduce the positive charge of the grains so that photoelectric heating is important. Consequently at high gas densities the pressure of the gas rises with increasing \( y \) in Figures 1, 2 and 3.

At intermediate gas densities the behaviour of the gas pressure is more complicated. In Figure 1 \( (\zeta_0 = 10^{-15} \text{ s}^{-1}) \) the peak pressure \( P_{\text{max}} \) rises with increasing \( y \) for all values of \( y \). In Figure 2 \( (\zeta_0 = 10^{-16} \text{ s}^{-1}) \) \( P_{\text{max}} \) first rises with increasing \( y \) but eventually drops so that for \( y = 1.0 \) it is almost reduced to its value for \( y = 0 \). This effect shows up even more dramatically in Figure 3 \( (\zeta_0 = 10^{-17} \text{ s}^{-1}) \). This interesting behaviour reflects the reduction of the photoelectric heating when the grains become strongly positively charged. In that case the heating rate depends non-linearly on the quantities \( n \), \( T \) and \( y \). This causes the reduced heating rate to decrease with increasing \( y \) (see Section III) and it leads to stabilization of the gas against thermal instability, as explained below.

![Fig. 1. The pressure of the interstellar gas as a function of the total Hydrogen density \( n \) for several values of the photoelectric emission efficiency of dust grains \( y = 0, 0.01, 0.1, 1.0 \). The primary cosmic ray ionization rate of atomic Hydrogen equals \( \zeta_0 = 10^{-15} \text{ s}^{-1} \). The tic marks indicate at which density photoelectric heating and cosmic ray heating are equal. The dots indicate at which density photoelectric heating becomes suppressed due to the charging up of the dust grains. Gas with densities in between a tic marc left and a dot right is stable against thermal instability.](image)

At intermediate gas densities the electrons in the gas are produced by cosmic ray ionization so that \( n(e) \approx (\zeta_0 n / \nu_0)^{1/2} \alpha (\zeta_0 n)^{1/2} T^{0.35} \). The asymptotic expressions of the photoelectric heating rate, derived in the preceding section, then lead to the following proportionality

\[ \Gamma_e \propto n \quad \text{for} \quad y < x_\gamma / 2 \]

and

\[ \Gamma_e \propto n^2 T^{-0.3} \quad \text{for} \quad y > x_\gamma / 2. \]

At intermediate gas densities the cooling rate of the gas is dominated by electron excitation so that

\[ \Lambda \propto n^2 (T^\alpha n^1.5 T^{\alpha + 0.35} \]

where \( \alpha \) is the logarithmic slope of the interstellar cooling curve. In thermal balance (\( \Gamma = \Lambda \)) the condition for thermal instability may be written (Field, 1965)

\[ \frac{dP}{dn} < 0, \]
i.e. the gas pressure decreases with increasing density. Expressing \( P \) as a function of \( n \) only by writing \( P \propto nT \) and eliminating \( T \) using the equation \( \Gamma_\alpha = A \) I find that the gas is thermally unstable if

\[-0.35 < \alpha < 0.15 \quad \text{for} \quad \gamma \ll x_d/2 \]

and if

\[-1.15 < \alpha < -0.65 \quad \text{for} \quad \gamma \gg x_d/2. \]

It is well known that for \( T \lesssim 10^4 \) K the logarithmic slope of the interstellar cooling curve has a lower limit \( \alpha > 0 \) (Dalgarno and McCray, 1972) so that the gas is always stable against thermal instability if photoelectric heating is reduced by the grain charge but still dominates the heating. In case the grains are not charged the thermal behaviour of the gas is similar for photoelectric heating and for cosmic ray heating because both depend in the same way on \( n \) and \( T \).

In order to illustrate how the curves in Figures 1, 2 and 3 are affected by the stabilization due to photoelectric heating I have indicated at which density photoelectric heating equals cosmic ray heating (by tic marks) and at which density photoelectric heating becomes affected by the grain charge (by dots). At the high density side of the tic marks photoelectric heating dominates, at the low density side of the dots photoelectric heating is suppressed. Thus the gas is stabilized against thermal instability at densities in between a tic mark left and a dot right. For example the curve for \( y = 1.0 \) in Figure 1 keeps on rising with increasing \( n \) until thermal instability can set in at the density where photoelectric heating is no longer suppressed by the grain charge. The same effect may be observed in Figures 2 and 3 for \( y = 0.1 \) and 0.01, respectively. Furthermore in Figure 2 the relatively small decrease in pressure from \( P_{\text{max}} \) to \( P_{\text{min}} \) for \( y = 1.0 \) is also due to stabilization of the gas against thermal instability because at \( P_{\text{min}} \) photoelectric heating takes over from cosmic ray heating. The same phenomenon may be observed for \( y = 0.1 \) in Figure 3.

In Figure 4 I show the separate contribution of all heating processes considered for the case \( \zeta_0 = 10^{-16} \) s\(^{-1} \) and \( y = 0.1 \). Photoelectric grain heating dominates for \( n > 0.2 \) cm\(^{-3} \) and \( \text{H}_2 \) photodissociative heating and Carbon photoelectric heating turn out to be unimportant throughout the range of densities considered. The changing dependence of grain heating on gas density is manifest. Figure 5 displays the run of temperature and electron density for the same case, \( \zeta_0 = 10^{-16} \) s\(^{-1} \) and \( y = 0.1 \).
V. A Variant of the Steady-state Two Phase Model

In this Section I shall attempt to determine which of the models, characterized by some combination of the parameters \( y \) and \( \zeta_0 \), gives the best fit to the observations. There to I reason as follows. From 21 cm observations of atomic Hydrogen (cf. discussion of Field, 1975) and from ultraviolet observations of molecular Hydrogen (cf. Spitzer and Jenkins, 1975) it is found that on the average interstellar clouds are characterized by \( n \approx 30 \text{ cm}^{-3} \) and \( T \approx 80 \text{ K} \). From my calculations I find that these values are reproduced for \( y = 0.1 \), virtually independent of the value of \( \zeta_0 \) because at this density the heating is dominated by photoelectric heating. With this value of \( y \) I fix \( \zeta_0 \) by requiring that the observed range of values of the intercloud gas density in the solar neighbourhood, \( 0.1 \leq n \leq 0.7 \text{ cm}^{-3} \), corresponds to pressures between \( P_{\text{max}} \) and \( P_{\text{min}} \) (Spitzer and Jenkins, 1975). The resulting value is \( \zeta_0 = 10^{-16} \text{ s}^{-1} \).

These values of \( y \) and \( \zeta_0 \) are comfortable for several reasons. From a survey of the literature on photoemission yields of several materials Watson (1972) suggested that the value of \( y \) is somewhere between 0.03 and 0.3 in agreement with later work of Feuerbacher and Fitton (1972). The value of \( \zeta_0 = 10^{-16} \text{ s}^{-1} \) that I obtain is about one order of magnitude below that required by previous steady state models (Field, 1975). This weakens the theoretical objections raised by Kulpsrud and Cesarsky (1971) against a high flux of low-energy cosmic rays, although \( \zeta_0 = 10^{-16} \text{ s}^{-1} \) may still be too high. Furthermore discussions of the observed HD and OH abundances in clouds (Black and Dalgarno, 1973; O'Donnell and Watson, 1974) have led to estimated upper limits to \( \zeta_0 \) of about \( 10^{-16} \text{ s}^{-1} \).

In Table 3 I have gathered some parameters of the model with \( y = 0.1 \) and \( \zeta_0 = 10^{-16} \text{ s}^{-1} \). There are several other observational quantities against which this model can be tested. In the first place, the temperature of the neutral intercloud gas. Recent 21 cm absorption line observations towards the strong radio continuum sources Cas A and Cyg A by Mebold and Hills (1975) have demonstrated the existence of a hot neutral Hydrogen gas with temperatures ranging from about 3000 \( \text{K} \) to about 8000 \( \text{K} \), in excellent agreement with the values in

<p>| Table 3. Gas parameters of the model with ( \zeta_0 = 10^{-16} \text{ s}^{-1} ) and ( y = 0.1 ) |
|------------------------------------------|-------|----------|------|-------|------|------|</p>
<table>
<thead>
<tr>
<th>( P/\text{cm}^{-3} \text{ K} )</th>
<th>( n(\text{cm}^{-3}) )</th>
<th>( n(\text{cm}^{-3}) )</th>
<th>( T(\text{K}) )</th>
<th>( n(\text{cm}^{-3}) )</th>
<th>( n(\text{cm}^{-3}) )</th>
<th>( T(\text{K}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4.5 \times 10^3(\text{max}) )</td>
<td>0.8</td>
<td>0.02</td>
<td>5000</td>
<td>0.05</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>( 2.2 \times 10^3 )</td>
<td>0.25</td>
<td>0.01</td>
<td>8000</td>
<td>0.03</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>( 1.3 \times 10^3(\text{min}) )</td>
<td>0.15</td>
<td>0.008</td>
<td>8000</td>
<td>0.02</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

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Table 3. Lower limits to the temperature of the intercloud gas of about 800 K had been determined earlier by Radakrishnan et al. (1971) from a comparison of emission and absorption spectra of atomic Hydrogen in many directions in the galaxy. The existence of a hot neutral intercloud gas has been questioned by Greisen (1973). However, his conclusions, based on aperture synthesis observations of hydrogen absorption lines in the direction of a few strong galactic radio continuum sources, are controversial (Lazareff, 1975; Mebold and Hills, 1975). Secondly, the electron density in the intercloud gas. Falgarone and Lequeux (1972) derived \( n(e) = 0.025 \text{cm}^{-3} \) from pulsar dispersion measures. The electron densities in Table 3 fall short of this value by at most a factor 3. I do not give much weight to this discrepancy in view of the contribution of individual H II regions to the electron density along any line of sight in the galaxy. Torres-Peimbert et al. (1974) have shown that there are sufficient ionizing photons from field OB stars to keep all intercloud gas ionized at a density of 0.2 \( \text{cm}^{-3} \). Thirdly, the electron density in interstellar clouds. An analysis of the ionization equilibria of several metals in interstellar clouds yields \( n(e) \approx 0.1 \text{cm}^{-3} \) (Field, 1975) a factor 3 or so higher than in the model in Table 3. This discrepancy is not very serious because all calculations to date refer to the gas at the boundary of the cloud. Models of interstellar clouds which are in hydrostatic equilibrium show that the total gas density and the electron density rise with depth into the cloud (de Jong and Dalgarno, 1977). Electron densities of about 0.1 \( \text{cm}^{-3} \) occurs deeper in the cloud (\( A_V \approx 0.5 \)) where the atomic and ionic lines are mainly produced. The same argument applies to the explanation of the low-frequency radio absorption of the interstellar gas. From his observations at 20 MHz Bridle (1969) derived \( x = 0.34 \text{kpc}^{-1} \). The parameters of the average interstellar cloud in Table 3 yield \( x = 9 \times 10^{3} n_e f_j T^{3/2} = 0.11 \text{kpc}^{-1} \) where I have inserted \( f_j = 0.10 \), the filling factor of clouds. The higher electron density and the lower temperature inside clouds easily account for the factor of 3 discrepancy between the model and the observations.

Finally I point at some attractive features of my model. The range of cloud temperatures and densities between \( P_{\min} \) and \( P_{\max} \) is in better agreement with the observations than in the cosmic ray heated model of Field et al. (1969). Molecular clouds forming in the compressed gas after passage of a spiral shock wave would be characterized by \( n \approx 100 \text{cm}^{-3} \) and \( T \approx 40 \text{K} \) at their boundaries (\( P_{\max} \)) while so called "standard clouds" with \( n \approx 10 \text{cm}^{-3} \) and \( T \approx 100 \text{K} \) (Spitzer, 1968) fall in the trough at \( P_{\min} \). The latter represent the final and longest living state of interstellar clouds before they evaporate into intercloud gas. Furthermore in my model the pressure of the interstellar gas is about a factor 3 or so higher than in previous models. This is partly due to the adopted depletion of the coolants and partly to the inclusion of photoelectric grain heating. Although the pressure is still not high enough to be in pressure equilibrium with the very hot \( 10^6 \text{K} \) component of the interstellar gas that is supposed to be the source of the soft X-ray background and the O VI absorption lines (Shapiro and Field, 1976) it is conceivable that in some variant of the class of models discussed here the required pressure of \( P/k \approx 2 \times 10^4 \text{cm}^{-3} \text{K} \) is attained.

Recently Jura (1976) has independently suggested that photoelectric heating could be an important heat source for the intercloud gas. His suggestion is based on quite different dust parameters, a photoelectric threshold energy \( h\nu_e = 4 \text{eV} \) and an electron emission probability \( \gamma = 0.67 \). With these parameters the photoelectric heating rate of the intercloud gas (\( \gamma > x_0/2 \)) is about equal to the heating rate calculated with the parameters that I have adopted (\( h\nu_e = 10 \text{eV}, \gamma = 0.1 \)) but the heating rate of the gas in clouds (\( \gamma < x_0/2 \)) would be a factor 300 larger which would result in unreasonably high cloud temperatures. It is clear from my Figures 2 and 3 that it is very difficult to explain the existence of a hot intercloud gas with heating by photoelectrons from dust grains if \( h\nu_e = 10 \text{eV} \) and \( \gamma \) is as large as suggested by Jura.

VI. Conclusion

In summary I conclude

(i) that heating by photoelectrons from dust grains can account for a hot neutral intercloud gas,

(ii) that the interstellar gas is stable against thermal instability when it is heated by photoelectrons from positively charged dust grains, and,

(iii) that reasonable agreement with the observed parameters of the interstellar gas can be obtained for a model which is characterized by \( \zeta_0 = 10^{-16} \text{s}^{-1} \) and \( \gamma = 0.1 \). This value of \( \zeta_0 \) is still somewhat high but it is consistent with present observational constraints.

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