

## HEATING OF INTERSTELLAR H I CLOUDS BY ULTRAVIOLET PHOTOELECTRON EMISSION FROM GRAINS

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### ABSTRACT

The physical processes and consequences of photoemission from interstellar grains in H I regions are investigated. For likely grain materials except ice, the photoemission is expected from laboratory data to be relatively efficient for photon energies of  $\sim 10$ – $13.6$  eV. It causes these interstellar grains to be positively charged in H I regions if the galactic ultraviolet flux is that indicated by recent observations. The ejected photoelectrons represent an energy input into interstellar H I clouds that is comparable to that from proposed fluxes of low energy cosmic rays or X-rays. Photoemission alone can maintain gas temperatures near  $50^\circ$  K in “standard” H I clouds. The exact value of the temperature depends on the grain density in the gas and the possible underabundance of carbon.

### I. INTRODUCTION

A number of investigations directed toward explaining the source of heating and ionization of the interstellar H I gas have been made based on steady-state models in which the proposed source is low-energy ( $\sim 2$  MeV) cosmic rays (e.g., Spitzer and Tomasko 1968; Pikel’ner 1968; Field, Goldsmith, and Habing 1969) or low-energy ( $\sim 70$ – $250$  eV) X-rays (Silk and Werner 1969). A time-dependent model in which the energy input is provided by periodic supernova outbursts has also been suggested (Boettcher *et al.* 1970). All the models seem to encounter most difficulty in explaining the heating (temperature  $\sim 50^\circ$  K) and perhaps ionization of H I clouds (Werner, Silk, and Rees 1970; Boettcher *et al.* 1970), particularly because of the very weak penetrating ability of low-energy cosmic rays and X-rays. Observationally it is not clear whether the rate of ionization (with consequent heating) in typical H I clouds (see Ball *et al.* 1970; Cesarsky 1971; Cesarsky and Cesarsky 1971; Chaisson and Goad 1972) is sufficient to produce an electron density equal to the observed average interstellar electron density ( $\sim 0.05$  electrons  $\text{cm}^{-3}$ , e.g., Terzian 1972).

Emission of photoelectrons from interstellar grains by galactic starlight serves to convert ultraviolet starlight energy into gas kinetic energy at a rate which we will show is likely to be substantially greater than that due to ultraviolet ionization of atoms in the gas, and comparable with the heating that results from proposed fluxes of low-energy cosmic rays or X-rays. This photoelectron emission also affects the charge of interstellar grains, which in turn determines the rate at which atoms that are ionized in interstellar H I regions stick to the grains. Of these atoms (C, Na, Si, Ca, Fe, etc.), carbon is especially interesting because of its importance in the formation of interstellar molecules (Watson and Salpeter 1972) and its possible depletion which would reduce the cooling rate of the interstellar gas (Field *et al.* 1969). If the grain charge is positive, the sticking rate is strongly inhibited.

Photoemission from interstellar grains in H I regions was investigated some time ago (Spitzer 1948). No information was available then on the galactic ultraviolet starlight, nor were laboratory data for photoemission available at photon energies greater than  $\sim 10$  eV. Except for special materials, photoemission from solids is relatively inefficient ( $\sim 10^{-3}$ – $10^{-5}$  electrons per photon) at the lower photon energies, and the process seemed

to be unimportant for heating of the gas or altering the charge of the grain. It has subsequently been ignored, and interstellar grains in H I regions are usually assumed to have negative charges as a result of the equilibrium between the sticking of electrons and positive ions (e.g., Spitzer 1968). Sufficient laboratory data have now accumulated to indicate that photoemission is appreciably more efficient (yield  $\sim 0.1$ ) for typical non-metals at the high photon energies ( $\sim 10$ – $13.6$  eV). Also, recent direct measurements from rockets (Hayakawa and Yamashita 1968), as well as theoretical investigations (Habing 1968) that use the latest data on stellar properties, provide information on the galactic ultraviolet radiation field.

Although the composition of interstellar grains is essentially unknown (§ II), the relevant physical properties (photoelectric yield, photoelectron energy distribution, and low-energy electron sticking; § III) are sufficiently similar that results (§ IV) are not sensitive to this uncertainty, as long as most grains are nonmetals and not ice. The basic theoretical ideas (§ II) have been discussed by Spitzer (1948). For calculational convenience an analytic model (§ III) is introduced, and the results for interstellar H I cloud conditions suggest that these clouds might be heated solely by photoemission from grains (§ V).

## II. BASIC IDEAS

### a) *Charge on Interstellar Grains*

The cross-section for a particle of charge  $q$  from an equilibrium gas (temperature  $T$ ) to hit a grain with electric potential  $V_0$  is determined from Coulomb trajectories, and is different from the geometric cross-section by a factor (Spitzer 1948)

$$1 - \frac{qV_0}{kT}, \quad qV_0 < 0; \quad \exp(-qV_0/kT), \quad qV_0 > 0.$$

The sticking of positively charged particles will be unimportant in the calculations here, so that the requirement of charge equilibrium on the grain leads to an expression for the electric potential  $V_0$ ,

$$\frac{eV_0}{kT} = \int F\gamma Q_{\text{abs}} dE_\nu / n_e v_e S - 1,$$

resulting from the balance between electron sticking from the gas and photoemission by ultraviolet photons. Here  $F$ ,  $\gamma$ , and  $E_\nu$  are the ultraviolet photon flux, photoemission yield, and photon energy; and  $n_e$ ,  $v_e$  are the electron density and thermal velocity. The photon absorption efficiency (absorption/geometrical cross-section) and electron-sticking probability (§ IIIb) are given by  $Q_{\text{abs}}$  and  $S$ . For the energies of the ejected electrons ( $\sim$ few eV), their excess energy (relative to  $kT$ ) is converted into heating of the interstellar gas with essentially complete efficiency (Spitzer and Tomasko 1968). Since the electric potential on interstellar grains can only be a few eV at most because of the cut-off in the galactic photon spectrum at 13.6 eV, the net charge is only  $10$ – $10^3$  electron charges whereas the grain has  $\sim 10^7$ – $10^9$  heavy atoms. The contribution to the electron density in the gas is then negligible.

### b) *Composition of Interstellar Grains*

The composition of interstellar grains, on which the photoemission properties depend somewhat, is essentially unknown. There is weak evidence against the ice (Knacke, Cudaback, and Gaustad 1969; Hunter and Donn 1971), and certain absorption features of grains near stars (where grains probably are formed) can be identified with silicates (Woolf and Ney 1969; Gillett, Merrill, and Stein 1971). Based on the amount of material needed to explain interstellar optical extinction together with cosmic abundances, and on the substances that might be expected to condense in the atmospheres of cool stars,

grain materials that have been suggested include mixtures of graphite, SiC, iron, MgO, Al<sub>2</sub>O<sub>3</sub>, quartz, MgSiO<sub>3</sub>, and other silicates (e.g., Gilman 1969; Hoyle and Wickramasinghe 1968, 1969; Gilra 1971; Wickramasinghe 1971). The grains are not likely to be mainly metallic (chiefly iron) because of the low cosmic abundance of metals in comparison with the mass needed for interstellar extinction (see Spitzer 1968). Interstellar grains probably have appreciable impurities, both in the interior and on the surface, and may have an amorphous structure due to constant bombardment by cosmic rays.

### III. PHOTOEMISSION AND STICKING OF ELECTRONS ONTO INTERSTELLAR GRAINS

#### a) Photoemission Properties of Grains

Extensive information on the photoemission yield from solids (photoelectrons per absorbed photon as a function of photon energy) and on the energy distribution of the photoelectrons is not available, except perhaps for metals and photocathode materials. However in the photon energy range  $\sim 10$ – $13.6$  eV, which is above the work function of most materials, yields seem to be mainly a function of band-gap energy (e.g., Sommer 1968). Materials with small band-gaps ( $\sim 1$  eV: semiconductors, graphite) seem to have yields  $\sim 0.03$  photoelectrons per absorbed photon (e.g., SiC [Sommer 1968]; Si [Pierce and Spicer 1971]), while good insulators with large band-gaps (ionic crystals, oxides) typically have yields  $\sim 0.1$ – $0.2$  in this energy range (e.g., MgO [Sommer 1968]; Al<sub>2</sub>O<sub>3</sub> [Pong 1969]; alkali halides [Taylor and Hartmann 1959]). Yields for metals can be less ( $0.01$ – $0.001$ ), though metals probably represent only a small fraction of grains, if they occur at all. For some molecular crystals, of which frozen H<sub>2</sub>O is an important case, the work function is near the Lyman edge and photoemission is much less efficient. The average energy of the ejected photoelectron also depends somewhat on the material and photon energy, but is typically about 2 eV for an average of the photon energies considered (e.g., Pierce and Spicer 1971; Taylor and Hartmann 1959). At these ultraviolet photon energies, surface impurities and adsorbed layers do not usually decrease the photoemission properties (e.g., Sommer 1968), nor does an amorphous structure (e.g., Pierce and Spicer 1971). (See Addendum, page 271.)

These laboratory measurements are made for photons normally incident onto a large plane surface. Since astrophysical grains are not large relative to ultraviolet wavelengths, the difference in the photon absorption (as a function of position) within the grain and within a plane surface must be considered. For this a model of photoemission is needed, and we follow Pepper (1970) in adopting a simplified probability of the form  $C \exp(-x/l_e)$  for emission of a photoelectron when a photon is absorbed at a distance  $x$  from the surface. Here  $l_e$  is the electron mean free path in the material and  $C$  is a constant that is determined from the yield, the complex refractive index  $m$  of the plane surface, and  $l_e$ . Probably, for good insulators  $l_e \sim 100$  Å (Pong 1966, 1967, 1969), for metals  $l_e \sim 10$ – $25$  Å (Pong *et al.* 1970; Gesell and Arakawa 1971), and for semiconductors  $l_e \sim 50$  Å, though these are measured in only a few cases and there is some disagreement especially for metals. Calculations involving the above form for the photoemission probability give agreement with experiment when applied to obliquely incident light in the case to which it has been applied (Gesell and Arakawa 1971). Using Mie scattering theory (e.g., van de Hulst 1957) to determine the fields inside the particle when a plane electromagnetic wave is incident on the grain, one can calculate the absorption as a function of radius (divergence of the Poynting vector  $S$ ) and determine the yield,

$$y = \int C \exp(-x/l_e)(\nabla \cdot S) dv / \int (\nabla \cdot S) dv ,$$

by integrating over the volume. We have done this for a spherical grain (other shapes have higher yields), for two representative values of  $m$  for likely grain materials in the ultraviolet ( $m = 2.5 + 1.0i$ ,  $1.4 + 0.8i$ ), for grain radii  $a = 0.025$ – $0.10$   $\mu$ , and for a

photon wavelength of 1000 Å. The result is not strongly sensitive to these parameters nor to  $l_e$  for  $25 \text{ Å} \lesssim l_e \lesssim 100 \text{ Å}$ . Small spheres are found to be more efficient than plane surfaces for photoemission by a factor  $y_{\text{sphere}}/y_{\text{plane}} \sim 2\text{--}3$  for these parameters.

### b) Sticking of Low-Energy Electrons onto Grains

As we will see below, grains (except ice or metals) are most likely to be positively charged (with positive potential  $V_0$ ), so that electrons hit the grain with a kinetic energy  $eV_0 + kT > kT$ . In H I clouds where  $kT \sim 0.002\text{--}0.01 \text{ eV}$ ,  $eV_0$  is a fraction of an electron volt so that the electron hits the surface with a kinetic energy only slightly less than its total energy. No data are available for such sticking on charged surfaces, but some exist for the sticking of low-energy ( $\sim \text{eV}$ ) electrons onto *neutral* surfaces. For metals, metals covered with a chemisorbed layer, and materials with a small band-gap (e.g., graphite, SiC) a sticking coefficient  $S$  near unity is indicated (Lander and Morrison 1964; Redhead, Hobson, and Kornelsen 1968). Data on good insulators exist only for a few ionic crystals and give values of  $S \sim \frac{1}{3}$  at incident kinetic energies of interest (Fredericks and Cook 1961, 1963). For the interstellar grains with the strongly attractive potentials,  $S$  is at least as great as for these neutral surfaces and is probably significantly greater. In addition, surface irregularities, surface impurities, and the disordered lattice of interstellar grains due to cosmic-ray bombardment and impurities tend to increase  $S$ . We therefore provisionally adopt a value  $S = 1$  for all positively charged interstellar grains in H I regions, whether they have small band-gaps or are good insulators.

### c) Approximations and Analytic Model

Based on the foregoing discussion, we adopt for interstellar grains that are neither metallic nor ice,  $y = 0.1$  and  $E_e$  (the average energy of an ejected electron)  $\sim 2 \text{ eV}$  for ultraviolet photons in the range 10–13.6 eV when the grain is uncharged. Also,  $S = 1$  is assumed. The estimate  $y = 0.1$  includes the enhanced efficiency (a factor of 2–3) due to the small size of grains. To perform calculations and include the influence of the positive electric potential  $V_0$  on photoemission, these assumptions are put in the form of a simplified analytic model in which

$$\begin{aligned} E_e &= E_\nu - 10.1 \text{ eV} - eV_0, \\ y &= 0.1, \quad E_\nu > 10.1 \text{ eV} + eV_0, \\ &= 0, \quad E_\nu < 10.1 \text{ eV} + eV_0; \end{aligned}$$

that is, charging of the grain is assumed simply to shift the threshold. We further assume that the ultraviolet photon spectrum is constant in the energy interval 10.1–13.6 eV to obtain a heating rate per hydrogen atom

$$H_{\text{H}} = 0.1 Q_{\text{abs}} \frac{n_0 \sigma_0}{\bar{n}} F_{\text{eV}} \frac{(3.5 - V_0)^2}{2}$$

Here  $n_0$ ,  $\sigma_0$ , and  $\bar{n}$  are the number density and cross-section for grains, and the number density of hydrogen, respectively. The photon flux per eV is expressed as  $F_{\text{eV}}$ .

## IV. APPLICATION TO INTERSTELLAR H I REGIONS

The ultraviolet photon flux for energies  $E_\nu = 10\text{--}13.6 \text{ eV}$  at a point in the galactic disk has not been measured. Theoretical calculations (Habing 1968) suggest a relatively flat (in wavelength) spectrum in the ultraviolet. Direct rocket measurements at slightly lower energies (8.4–9.2 eV) give a value  $1.8 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \text{ sterad}^{-1}$  for the angular averaged flux (Hayakawa and Yamashita 1968; Hayakawa, Yamashita, and Yoshioka 1969) and results in agreement with these measurements at high galactic latitudes (Henry 1971) have recently been obtained. These data disagree with another

observation (Kurt and Sunyaev 1968). We adopt the value of Hayakawa *et al.* as a representative value for the flux in the 10–13.6 eV region, also.

In figure 1 we show the electric potential of interstellar grains based on the model of § III and the above ultraviolet flux for several temperatures and electron densities that are likely to occur in interstellar H I regions (both cloud and intercloud conditions). Theoretical models for the interstellar gas in which the proposed source of heating and ionization is the low-energy cosmic rays or X-rays suggest that the gas can be divided into low-density intercloud regions ( $T \sim 10^3$ – $10^4$  °K) and higher-density clouds ( $T \lesssim 10^2$  °K) that have approximately the same electron densities (e.g., Bergeron and Souffrin 1971). The models assume that the cosmic rays or X-rays do penetrate the clouds, though theoretically and observationally this is unclear (see § I). For these models the appropriate value of  $n_e$  for figure 1 is roughly the interstellar average electron density ( $\sim 0.05$  cm $^{-3}$ ). A lower limit on the electron density in clouds is obtained from the ionization by starlight of atoms with ionization potentials less than 13.6 eV and gives  $n_e \sim 5 \times 10^{-4} \bar{n}$  for cosmic abundances. Ionization by the observed higher-energy cosmic rays or X-rays produces a significantly greater electron density than starlight under low-density intercloud conditions (see Spitzer and Tomasko 1968; Silk and Werner 1969). Thus figure 3 below indicates that likely interstellar grains (except ice) are probably positively charged as long as the ultraviolet starlight is unshielded. However in H I clouds of modest optical extinction, the ultraviolet is severely attenuated, and we have suggested elsewhere (Watson and Salpeter 1972) that this reduction factor at a point in a cloud is  $\sim \exp(-2.5\tau_v)$ , where  $\tau_v$  is the (visible) optical depth from the point to the edge of the cloud. Then for clouds of density  $\bar{n} \sim 10^3$  cm $^{-3}$  with electrons produced only by ionization by starlight, these grains will be negatively charged for  $\tau_v \gtrsim \frac{1}{2}$ .

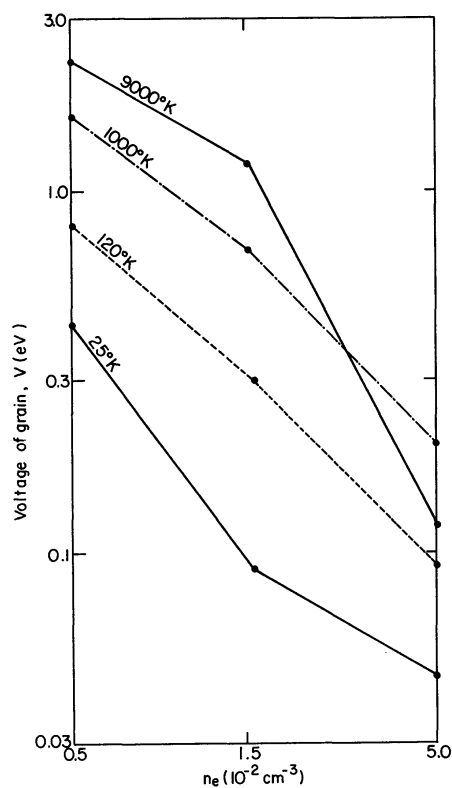


FIG. 1.—Electric potential  $V_0$  of interstellar grains in H I regions as a function of electron density  $n_e$  for representative gas temperatures.

To compare the energy input with that needed for heating the interstellar gas in intercloud H I regions, we present the heating ( $n_e \bar{n} H_{ei}$  ergs cm<sup>-3</sup> s<sup>-1</sup>) and cooling ( $n_e \bar{n} L_{ei}$ ) rates in figure 2 in the form of a graph of  $H_{ei}$  and  $L_{ei}$ . The cooling rate  $L_{ei}$  is taken from Pikel'ner (1968). Curves for representative values of the other variables are shown.

Since to some extent the purpose of this calculation is to investigate an alternative mechanism for heating H I clouds if the source of ionization for the intercloud region does not affect the clouds, an electron density for ionization by starlight only ( $n_e = 5 \times 10^{-4} \bar{n}$ ) is used in the calculation of cloud temperatures. The dominant cooling mechanism under these conditions is excitation of fine-structure levels of C II and O by hydrogen atoms; and we adopt the rates of Goldsmith, Habing, and Field (1969) for these processes, ignoring other processes. Cosmic abundances are taken as representative values. The resulting gas temperatures are shown in figure 3 for two choices of the grain density, as well as for a lower abundance of the heavy atoms that provide the cooling. The electron density is also reduced appropriately in this latter case. For an increase (decrease) in ultraviolet flux or  $\gamma$ , the resulting  $T$  versus  $\bar{n}$  curve is obtained from figure 3 by shifting the appropriate curve to higher (lower) values of  $\bar{n}$  by the same factor as the change in ultraviolet flux or in  $\gamma$ . A higher electron density than assumed will affect the calculations both by enhancing the efficiency of the photoemission (by reducing the voltage barrier) and by increasing the cooling as a result of excitation of fine-structure levels by electrons. However, until the electron density is high enough that cooling due to these excitations is comparable with that due to excitations by hydrogen (for this,  $n_e/\bar{n} \approx 2 \times 10^{-4} \sqrt{T}$ ), the curves in figure 3 are a good approximation.

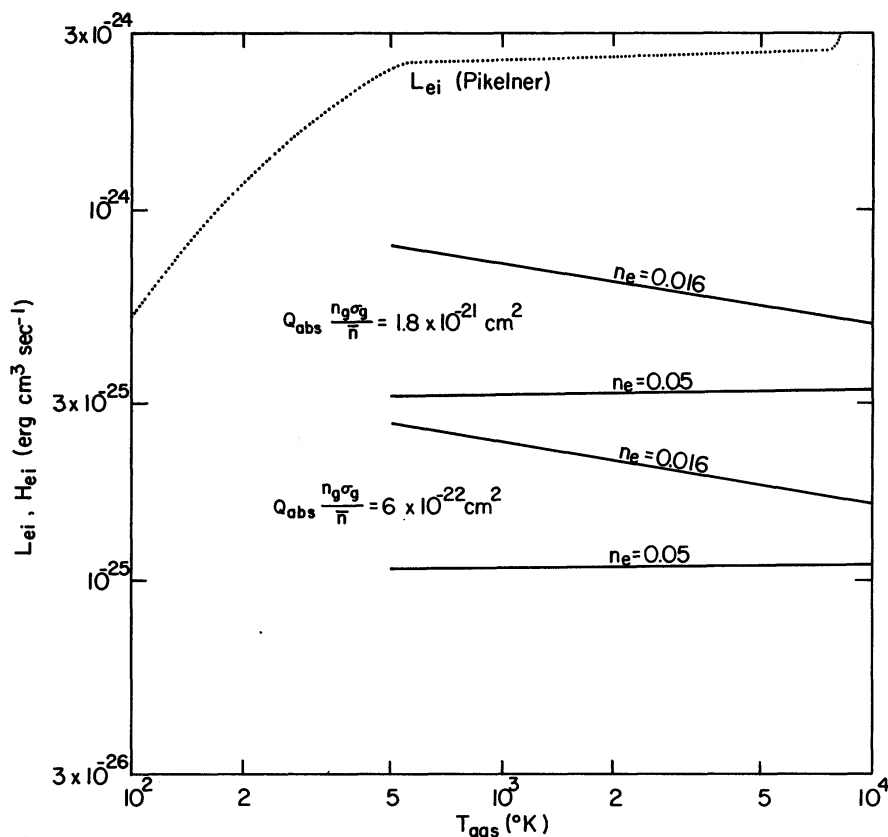


FIG. 2.—Heating ( $H_{ei}$ ) and cooling ( $L_{ei}$ ) rates for gas temperatures  $T_{gas}$  and electron densities  $n_e$  representative of intercloud H I regions. Grain-absorption surface area to hydrogen particle density is given by  $Q_{abs} n_g \sigma_g / \bar{n}$ .

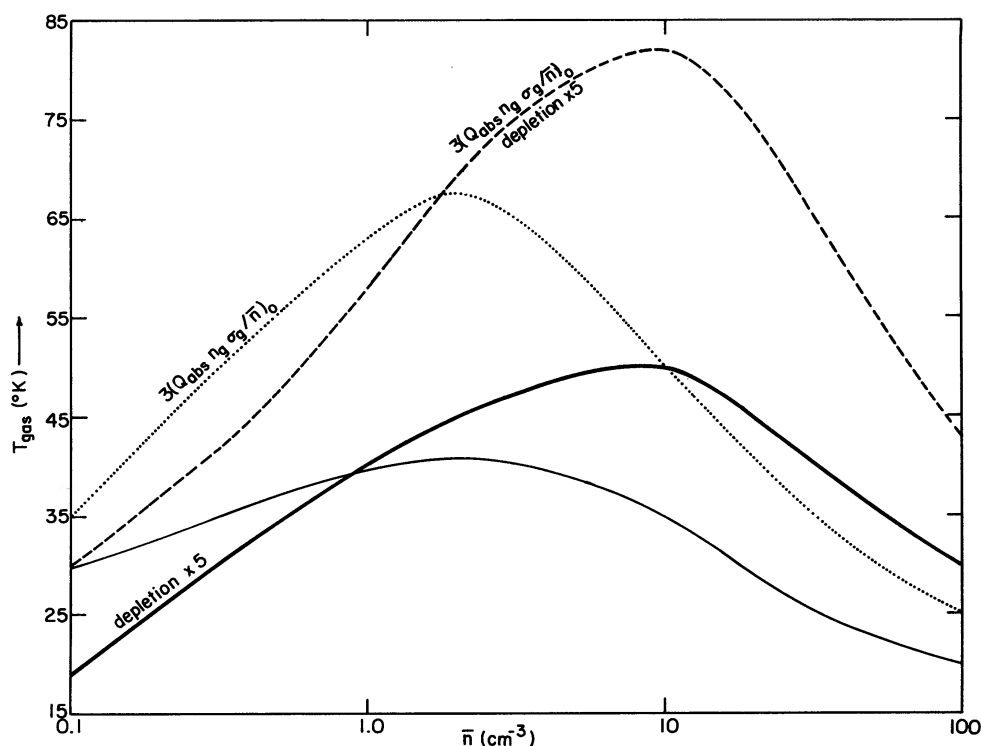


FIG. 3.—Equilibrium temperatures for interstellar H I clouds resulting from heating by photoemission from grains. Unmarked curve gives temperatures for heavy elements in cosmic abundance and a value for grain absorption surface area to hydrogen particle density  $Q_{\text{abs}}n_g\sigma_g/\bar{n}$  of  $6 \times 10^{-22} \text{ cm}^2$ . Other curves give temperatures for underabundance of heavy elements and for a higher grain density. Electron density  $n_e$  is  $5 \times 10^{-4}$  of the hydrogen particle density  $\bar{n}$ .

#### V. DISCUSSION

The condition that grains be positively charged ( $1 < \int Q_{\text{abs}} F_{\nu} dE_{\nu} / n_e v_e S \sim 1/n_e$  in H I clouds) seems to be strongly satisfied for likely grain materials except ice (against which there is some evidence, § II) in “normal” H I clouds with little extinction, even if the electron density in clouds is as large as the interstellar average value ( $\sim 0.05 \text{ cm}^{-3}$ ). This causes difficulty for formation of molecules containing carbon on grains (Watson and Salpeter 1972) in unshielded clouds since interstellar molecules containing carbon are common and carbon is ionized. The sticking rate of singly charged ions is reduced by a factor  $\exp(eV_0/kT)$ , and  $eV_0/kT \gtrsim 10$ . The fractional abundance of neutral carbon (whose sticking would not be inhibited) in H I clouds is  $[C]/[C^+] \sim n_e/10$  (Werner 1970)  $\lesssim 10^{-2}$ . Similar difficulties with regard to depletion of carbon in clouds (Field *et al.* 1969) exist, though depletion might occur when the gas is processed through stars or in a dense cloud phase.

Although the observed temperatures of normal H I clouds are uncertain and probably differ for various clouds, values near  $50^\circ \text{ K}$  are typical (e.g., Radhakrishnan and Murray 1969). From figure 3 it is clear that heating by ultraviolet photoemission alone can maintain such temperatures for reasonable values of the relevant parameters. The lower value of  $Q_{\text{abs}}n_g\sigma_g/\bar{n}$  comes from a model to fit the interstellar extinction curve (Gilra 1971), and the higher value is consistent with the ratio of optical extinction to 21-cm absorption (Rohlfs 1971) together with the observed increase in extinction from the optical to the ultraviolet (Bless and Savage 1972). For this latter estimate the scattering efficiency  $Q_s$  for grains is taken to be zero in the visible, whereas in the ultraviolet  $Q_s$  and  $Q_{\text{abs}}$  are

assumed equal. Underabundance of heavy elements in the gas has been suggested by others to aid in explaining H I cloud temperatures (Field *et al.* 1969). The actual heating rate due to photoemission from grains is roughly  $10^{-14}$  eV per H atom per second, and is similar to that which would result from the proposed low-energy cosmic ray or X-ray fluxes. Photoelectric emission from atoms in the gas provides heating at a rate  $\sim 5.10^{-4}\alpha n_e \sim 3 \times 10^{-18}\bar{n}$  eV per H atom per second, where  $\alpha$  is the recombination coefficient for carbon (e.g., Werner 1970) and  $n_e$  has again been taken as  $5 \times 10^{-4}\bar{n}$ .

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