PHOTOELECTRON EMISSION FROM INTERSTELLAR GRAINS*

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Abstract. Photoelectric emission from interstellar dust grains due to ultraviolet starlight is reinvestigated. Ejection of photoelectrons can make a substantial contribution to the heating of standard interstellar clouds. Both positive and negative grain charges are shown to be possible.

1. Introduction

The emission of photoelectrons from interstellar dust grains in H I regions by absorption of ultraviolet starlight (energy $\approx$ 10–13.6 eV) is of chief interest at present because it influences the electric charge on the grain and provides a mechanism for converting starlight energy into gas kinetic energy. Also, the force on a grain resulting from photoemission can be comparable or greater than that due to the usual radiation pressure in both H I and H II regions.

The charge on grains is determined by an equilibrium resulting from the sticking of positive charges (mainly protons or carbon ions) and electrons, and the ejection of electrons by the photoelectric effect. Since the early investigation of Spitzer (1948), photoemission has been considered to be negligible so that the charge on interstellar grains has been thought to be slightly negative $e\phi/kT_{\text{gas}} \approx -2.5$, where ϕ is the potential of the grain, T_{gas} is the gas temperature and k is Boltzmann's constant. This analysis was however based on the photoemission data at relatively low photon energies ($\lesssim$ 5 eV) available at that time. Since then, laboratory investigations have established that photoemission is much more efficient at ultraviolet energies ($\approx$ 10–13.6 eV). If interstellar grains have appreciable positive charges, molecule formation on grains (see Watson and Salpeter, 1972a, b) involving atoms that are ionized in the interstellar gas is inhibited since the sticking of these ions to grains is reduced by a factor exp $(-e\phi/kT_{\text{gas}})$. Carbon is an important example. Photoelectrons typically have kinetic energies of a few eV and this can represent a source of heating to the gas since $kT_{\text{gas}} \approx$ 0.01 eV in interstellar H I clouds. This heating may be significant in 'standard' clouds. The properties of the grain material that determine the charge and heating are then the photoemission yield (photoelectrons/absorbed photon), the photoelectron energy distribution, and the sticking coefficient S for low energy (0.01 eV) electrons to attach themselves to a grain. In addition a knowledge of the average interstellar starlight

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flux in the (10–13.6) eV range, the electron density N_e and the total absorption cross section of grains $Q_{abs}N_g\sigma_g N_H$ cm^{-2} per H atom is necessary. We discuss these factors in the remainder of the paper, as well as in a previous article (Watson, 1972, hereafter referred to as Paper I) in somewhat more detail.

2. Relevant Properties of Interstellar Grains

Although neither the material composition of the grains is known, nor is photoemission data available for all potential grain materials, some generalizations fortunately are possible. The most frequently mentioned grain materials seem to be silicates, oxides, silicon carbide, graphite and ices, of which the last is most likely to occur as a

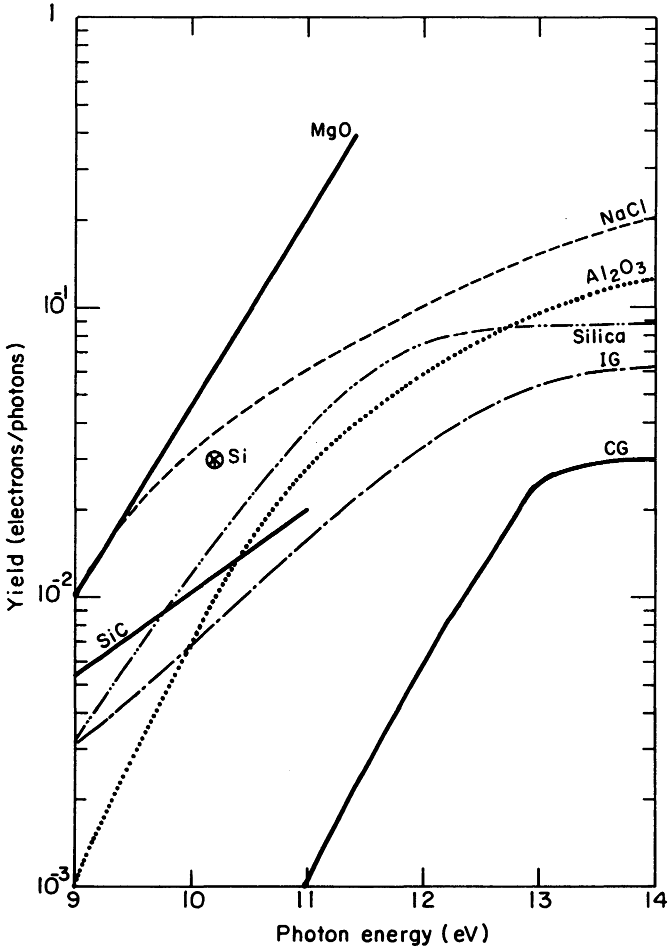

Fig. 1. Photoemission yields for representative grain materials, sources: MgO, Stevenson and Hensley (1961); NaCl, Taylor and Hartmann (1959); Al_2O_3, Pong (1969); silica, 'irregular' graphite (IG), and clean graphite (CG), Feuerbach and Fitton (1972); Si, Pierce and Spicer (1971); SiC, see Sommer (1968).

mantle on a core of one of the other materials. Frozen CH_4, NH_3, and especially H_2O are good candidates for the ices. These have thresholds for ionization near 13.6 eV were the interstellar radiation is cut off, so that photoemission from these is expected to be unimportant. There is some observational evidence against frozen H_2O on grains (Knacke *et al.*, 1969). For the other materials, except perhaps graphite, photoemission yields of $\approx$ (0.03–0.2) electrons/photon are expected (see Paper I and Figure 1). Data have recently become available for graphite and the yield in the pure form is much lower than anticipated by analogy with other material having small band-gaps. The actual yield of graphite is increased by irregularities in the crystal structure and probably by impurities, both of which most likely occur in interstellar grains (see Paper I). In Figure 1 we have summarized the data on yields from various materials representative of interstellar grains. These laboratory data are for radiation normally incident onto large plane surfaces. Because the size of a grain is comparable to ultraviolet wavelengths, the yield from a grain is not necessarily the same as from a plane. In Paper I and elsewhere (Watson, 1973) we have examined this effect. Under some conditions (especially for small grains) the yield can be enhanced by a factor of two or more over laboratory data. Representative distributions for the kinetic energy of the ejected electrons are shown in Figure 2.

Little data are available for the sticking coefficient S for very low energy ($\lesssim$ 1 eV) electrons from the gas onto surfaces. We are mainly interested in the case where photoemission is efficient and here the grain will assume an appreciable positive

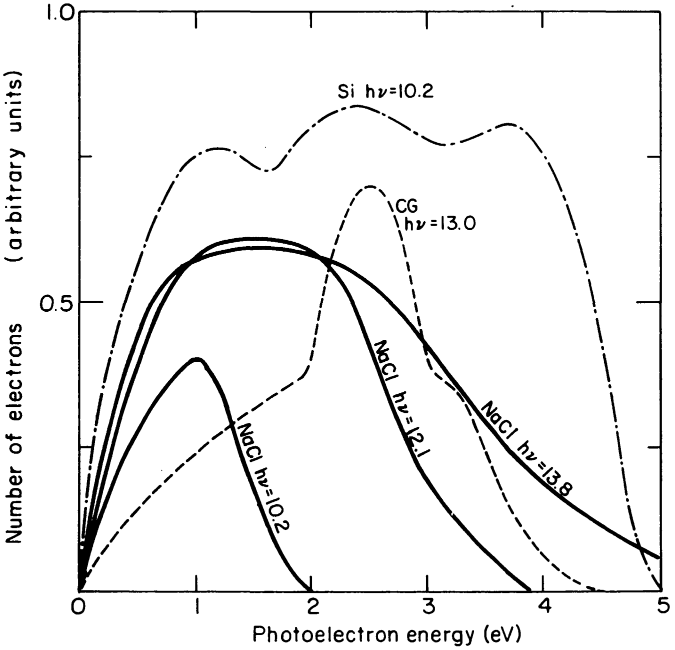

Fig. 2. Typical electron energy distributions for photoemission at representative photon energies $h\nu$ (see sources and notation in Figure 1).

potential (a few tenths eV) so that $e\phi \gg kT_{\text{gas}}$. On neutral surfaces, data suggest that for incident electron energies of about an eV, $S \gtrsim \frac{1}{3}$ (see Paper I). Hence for $e\phi \gg kT_{\text{gas}}$, probably $S \approx 1$.

In principle, the electron energy distributions should be integrated over all photon energies and electron energies E for $E > e\phi$ to obtain the effective yield and energy input into the gas. However such a detailed treatment is not warranted in view of the uncertainties in the various factors. Hence we introduce in Paper I an approximate model for the heat input H and the photoemission yield y that incorporates the above information.

$$H = 0.1(N_g \sigma_g Q_{\text{abs}}/N_{\text{H}}) F_{\text{eV}} \frac{(3.5 - e\phi)^2}{2}$$

$$(\text{eV per H atom s}^{-1}).$$

and

$$\begin{aligned} y &= 0.1, \qquad h\nu > 10\,\text{eV} + e\phi \\ &= 0, \text{ otherwise} \end{aligned}$$

($h\nu$ = photon energy) for materials other than ice. The photon flux per electron volt at (10–13.6) eV is given by F_{eV}, and N_g, N_{H}, σ_g and Q_{abs} are number densities of grains and hydrogen, the grain cross section, and the absorption efficiency for these ultraviolet photons.

3. Astrophysical Applications

The remaining factors needed are the interstellar starlight flux in H I regions at energies (10–13.6) eV, the electron density N_e, and for heating the gas $N_g \sigma_g Q_{\text{abs}}/N_{\text{H}}$. No direct measurements of average starlight have been made in this region, though there are measurements to 9.2 eV (see Hayakawa *et al.*, 1969). Semi-theoretical calculations suggest a relatively flat spectrum (in wavelength) to 13.6 eV (Habing, 1968). We therefore adapt in our calculations the value of Hayakawa *et al.* and assume a flat spectrum to 13.6 eV. Roughly the maximum electron density N_e is that given by pulsar dispersion measurements $N_e \approx 0.05\,\text{cm}^{-3}$ (see Terzian, 1972). In H I clouds N_e may be much smaller, roughly that due to ionization by starlight $N_e \approx 5 \times 10^{-4}\, N_{\text{H}}$ for cosmic abundances (see Paper I). The grain density ($N_g \sigma_g Q_{\text{abs}}/N_{\text{H}}$) is also uncertain by factors of about three and two representative values are used in our calculations.

The results of these calculations are presented in Paper I, and indicate that standard H I clouds can be maintained at temperatures in agreement with observations by this heating mechanism. The grain voltages are always positive and equal to a fraction of an electron volt. Because of the possible importance of graphite as a grain material, we have performed detailed calculations using the yield data for clean, ordered graphite (Feuerbach and Fitton, 1972). Any enhancement of y due to the small size of the particle is ignored and the above photon flux is used. For this very low photoemission yield (which is not likely to be the actual case), the grain is essentially neutral for $N_e \approx 0.05\ \text{cm}^{-3}$ and $S \approx 1$.

Ejection of photoelectrons causes a force on a grain as a result of the momentum given to the photoelectron. For a symmetric particle in an isotropic radiation field the net force is zero. However, the radiation may not be isotropic due to shielding by a nearby cloud or another grain, or because the grain is near a hot star (an H II region). The grain is then accelerated (see Spitzer, 1968). In the average radiation field, the ratio of the net force on a grain due to photoemission to that due to the usual radiation pressure is $\approx \frac{1}{2}(Q_{\text{uv}}/Q_{\text{opt}})(f_{\text{uv}}/f_{\text{opt}})$. The ultraviolet and optical absorption efficiencies Q_{uv} and Q_{opt}, and the factors by which the radiation is anisotropic in the ultraviolet and in the optical are such that the ratio is almost certainly greater than one (the ultraviolet is more readily absorbed and shielded). In H II regions the relative flux of ultraviolet radiation ($h\nu > 10$ eV) is much greater than in the average interstellar radiation field, so that photoemission is always the dominant force on grains resulting from absorption of photons in H II regions.

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