ABSTRACT

We discuss the forces on grains exposed to anisotropic radiation fields, including the usual “radiation pressure” force and also recoil forces due to photoemitted electrons, photodesorbed hydrogen atoms, and hydrogen molecules which form on the grain surface. We show that these forces can lead to grain dynamics in photodissociation regions which result in enhanced dust-to-gas ratios. Since the gas heating is probably dominated by photoelectric emission from dust, this might explain the unusually high gas temperatures inferred from ISO observations of molecular hydrogen in photodissociation regions.

Key words: dust; photodissociation regions.

1. INTRODUCTION

Far ultraviolet radiation incident on a cloud of molecular material dissociates molecules, giving rise to a surface layer of largely atomic material, called a photodissociation region (PDR). When a hot star is located near a molecular cloud, much of the star’s radiant output is absorbed and reprocessed in the resulting PDR. Dust in the PDR efficiently absorbs UV photons, which results in thermal IR emission. The warm gas cools via forbidden transitions in metal atoms and ions and via rovibrational transitions in H₂. Thus, the conditions in PDRs are probed observationally by IR studies. Many theoretical PDR models have been developed, and include quantitative determinations of IR diagnostics (e.g. Tielens & Hollenbach 1985; Draine & Bertoldi 1996; see also the review by Hollenbach & Tielens 1997 and references therein). The detailed understanding of PDRs will yield information on the structure of molecular clouds and their interaction with young stars, and thus ultimately on the process of star formation.

As discussed by Draine & Bertoldi in this volume, observations with the ISO short wavelength spectrometer have yielded the H₂ rotational distribution functions in PDRs, from which surprisingly high values of gas temperature (500 – 1000 K) have been inferred. It is not yet clear what heating processes are able to maintain the gas at such high temperatures. Photoelectric emission from dust grains is expected to be a major mechanism, but calculated heating rates are inadequate. Here we consider the possibility of enhanced dust-to-gas ratios in PDRs, which would imply increased photoelectric heating rates.

2. GRAIN DYNAMICS

Enhanced dust-to-gas ratios can result when grains drift with respect to the gas. We will begin by describing the motion of the gas (see Figure 1). Ionizing radiation from the hot star located near the molecular cloud (MC) photoevaporates material at the cloud surface, which then expands into the intercloud medium in a photoevaporative flow (PF). Thus, the ionization front propagates into the cloud. In our analysis, we adopt the frame of reference in which the ionization front is stationary; in this frame material flows through the PDR.

Figure 1. The physical picture.

If no other forces acted on the grains, they would simply be dragged along by the gas. However, there are forces associated with the anisotropic stellar UV ra-
radiation field. In addition to the usual “radiation pressure” force due to absorption and scattering ($F_{\text{rad}}$), there are also recoil forces, due to photoemitted electrons ($F_{\text{pe}}$) and due to photodesorbed adatoms and H$_2$ molecules which form on the grain surface ($F_{\text{pd}}$). As a consequence of these “radiative” forces, the grains drift with respect to the gas, at speed $v_{\text{drift}}$. If the gas moves at speed $v_0$ with respect to the ionization front then the grains move at speed $v_0 - v_{\text{drift}}$. Deep within the PDR, where the stellar UV has been attenuated, $v_{\text{drift}} = 0$. The grain overdensity near the ionization front is obtained using the continuity equation:

$$\frac{n_i}{n_0} = \left(1 - \frac{v_{\text{drift},i}}{v_0}\right)^{-1}, \quad (1)$$

where $n_0$ ($n_i$) is the grain number density deep within the PDR (near the ionization front) and $v_{\text{drift},i}$ is the drift speed near the ionization front; we assume one-dimensional flow and ignore magnetic fields. Since the drag force is roughly proportional to the drift speed, the overdensity is also given by

$$\frac{n_i}{n_0} = \left(1 - \frac{F_{\text{tot}}}{F_{\text{stop}}}\right)^{-1}, \quad (2)$$

where $F_{\text{tot}}$ is the sum of the radiative forces near the ionization front and $F_{\text{stop}}$ is the magnitude of the radiative force which would result in $v_{\text{drift}} = v_0$ (in which case the grains would be stopped near the ionization front).

3. EVALUATION OF RADIATIVE FORCES

Throughout, we assume spherical grains, so that Mie theory can be applied for the grain optics.

3.1. Radiation Pressure Force

The radiation pressure force is given by

$$F_{\text{rad}} = \pi a^2 \int_0^{\nu_\text{H}} d\nu \, u_\nu \left[Q_{\text{abs}} + Q_{\text{sca}} \left(1 - \langle \cos \theta \rangle \right)\right], \quad (3)$$

where $a$ is the grain radius, $\nu_\text{H} = 13.6$ eV/$h$, $u_\nu$ is the radiation energy density per frequency interval, and $\langle \cos \theta \rangle$ is the usual scattering asymmetry factor. We compute the absorption and scattering efficiency factors, $Q_{\text{abs}}$ and $Q_{\text{sca}}$, respectively, using a Mie theory code derived from BHMIE (Bohren & Huffman 1983) with dielectric functions as described by Draine & Lee (1984) and Laor & Draine (1993).

3.2. Photoelectric Force

We adopt a physical model for the photoelectric emission process (see Bakes & Tielens 1994, Weingartner & Draine 1999a). Of course, the photoemission rate and the total energy of the emitted electrons depend on the grain’s ionization potential, $IP$; for simplicity we take the electron energy $E_{\text{el}} = (\nu - IP)/2$, where $\nu$ is the energy of the absorbed photon. The ionization potential depends on the grain charge; the charge distribution is determined by the rates of electron attachment by accretion from the gas and removal by photoemission. Thus, the average photoelectric force depends on the ambient conditions; including the spectrum and energy density of the radiation and the gas density, ionization, and temperature; through their effects on the charge distribution. For a fixed charge state, the force is given by

$$F_{\text{pe}} = \pi a^2 \int_{\nu_\text{z}}^{\nu_\text{H}} d\nu \, \frac{\nu u_\nu}{h \nu} AY Q_{\text{abs}} S \sqrt{2m_e E_{\text{el}}}, \quad (4)$$

where $\nu_z = IP/h$, $Y$ is the photoelectric yield, the emission asymmetry factor $A(\nu, a)$ measures the asymmetry in the emission of photoelectrons over the grain surface, the recoil suppression factor $S$ accounts for electron emission in directions other than the surface normal, and $m_e$ is the electron mass.

We follow the simple prescription of Kerker & Wang (1982) for determining the asymmetry factor $A$. The probability of photoemission from any site on the surface is taken to be proportional to the electric intensity $|E|^2$ just below the surface at that point. Thus,

$$A(\nu, a) = \frac{-\int_{0}^{\pi} \sin \theta \cos \theta |E(\theta)|^2 d\theta}{\int_{0}^{\pi} \sin \theta |E(\theta)|^2 d\theta}, \quad (5)$$

where $\theta$ is the polar angle with respect to the direction of the incident radiation. In Figure 2 we display $A(\nu, a)$ as a function of incident photon energy for graphite grains of various sizes.

![Figure 2. The emission asymmetry factor $A$ as a function of the incident photon energy $\nu$, for graphite grains. The grain radius is indicated for each curve.](image)

In determining the recoil suppression factor $S$ we assume that the electrons emerge symmetrically with respect to the local surface normal, with a “cosine-law” angular distribution (i.e. the emission rate
at angle $\psi$ with respect to the surface normal $\propto \sin \psi \cos \psi$). For an uncharged grain, this would imply $S = 2/3$. When the grain is charged, the electron escapes on a hyperbolic trajectory, so that when it is at infinity its velocity vector makes an angle $\psi_\infty$ with respect to the surface normal which differs from the corresponding angle at the surface, $\psi$. See Weingartner & Draine (1999b) for the detailed calculation.

3.3. Photodesorption Force

In our simple model, we consider the exchange of hydrogen between the gas phase and the grain surface. We assume that the surface is entirely covered with chemisorption sites, as would be the case for bare graphite or silicate grains without ice mantles. When a gas phase H atom strikes the grain surface, it arrives either at an empty site or at a site which is already occupied by an adsorbed H atom. In the former case, it occupies the site with some sticking probability; otherwise it reflects and remains in the gas phase. In the latter case, it recombines with the resident H with some recombination probability; otherwise it reflects and remains in the gas phase. We assume that H$_2$ formed on the grain surface is immediately ejected from the grain. Adatoms are removed from the grain surface via recombination and photodesorption.

Suppose that the grain’s spin axis is aligned with the direction of the radiation anisotropy. Since the photodesorption rate is greater in the illuminated hemisphere than in the non-illuminated hemisphere, relatively more H leaves the surface as atoms in the former and as molecules in the latter. A net recoil force is expected, for two reasons. First, the total number of particles leaving the illuminated hemisphere exceeds that for the non-illuminated hemisphere. Second, the outgoing atoms likely carry a different momentum than the outgoing molecules. A net recoil force of zero is possible, but only if the momenta and sticking and recombination probabilities conspire to have the right values. The photodesorption force is greater when the spin axis makes a non-zero angle with respect to the radiation direction, since H which arrives at non-illuminated sites can be transported to illumination and photodesorbed. For a fuller discussion of the adopted values for relevant parameters and the details of the calculation, see Weingartner & Draine (1999b).

4. THE S140 PDR

Timmermann et al. (1996) studied the PDR associated with the S140 H II region using ISO and concluded that the gas temperature is $\gtrsim 500$ K. We have evaluated the radiative forces for graphite and silicate grains and the conditions in this PDR. To determine $F_{\text{stop}}$, we employed the expression for $F_{\text{drag}}$ in Draine & Salpeter (1979) and evaluated $v_0$ using a highly simplified model for the flow in the PDR; see Weingartner & Draine (1999b) for details. We display the ratios of the radiative forces to $F_{\text{stop}}$, as a function of grain size, in Figures 3 and 4.

5. CONCLUSIONS AND FUTURE WORK

For the S140 PDR, the forces associated with the anisotropic radiation are apparently large enough to result in significant grain overdensities. It is important to note, however, that the total radiative force is highly uncertain, due to uncertainties in the microphysics of the photoemission and photodesorption processes.

Our program of study will include an examination
of more PDRs and also simulations of the dynamics which result when $F_{\text{tot}} > F_{\text{stop}}$; i.e. when the grains near the ionization front are actually pushed deeper into the PDR. In this case, the further upstream a grain is pushed, the less effective the push, because the radiation is attenuated by other grains downstream. Also, we will add magnetic fields to the analysis. Finally, of course, we will estimate the implications for gas heating.

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