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PHOTOLEVITATION OF DIFFUSE CLOUDS

JOSÉ FRANCO,[1,2] FEDERICO FERRINI,[3] ANDREA FERRARA,[4] AND BRUNO BARSELLA[3]

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ABSTRACT

Radiation pressure on dust grains can raise small dusty clouds above the main gaseous disk to high Galactic latitudes. This "photolevitation" effect drives neutral gas and dust into a soft Galactic fountain, and can maintain a column density of the order of 10^{20} cm^{-2} above the main gaseous disk. This value is defined by dust opacity and corresponds to a normal dust-to-gas ratio with cosmic abundances. The maximum height reached by the photolevitated clouds depends on the radiation field and dust-to-gas ratios. Clouds located above luminous stellar clusters or near spiral arms with intense star formation can reach several hundred parsecs in height. This model may explain some observational evidence for the presence of dust mixed with gas at high latitudes in the Milky Way and in external galaxies.

Subject headings: galaxies: interstellar matter — interstellar: grains

I. INTRODUCTION

The dynamical evolution of small solid particles in interstellar space has been studied, beginning with some pioneering works in the 1930s (see Spitzer [1941] and references therein), under a variety of different conditions. Aside from the intensity of the radiation field, a key parameter of the evolution is the coupling between gas and dust. This coupling depends on the grain properties and the physical state of the gas (e.g., Spitzer 1978; Draine and Salpeter 1979): the time scales for momentum transfer in grain-gas interactions are sensitive functions of the gas density and grain charge. If gas drag is negligible, the pressure from strong radiation sources can accelerate dust grains to large velocities (e.g., Wolfe *et al.* 1950). Similarly, bare grains reaching the scale height of the gaseous disk can be ejected out of their host galaxy by starlight (e.g., Chiao and Wickramasinghe 1972; Barsella *et al.* 1989; Ferrara *et al.* 1989). When the gas-dust coupling is important, a net momentum transfer from the radiation field to the gas takes place and the gas is accelerated (radiation exerts a negligible force directly on the gas; Pecker 1974). This process seems to be the driving agent of massive winds from cool giant stars (e.g., Salpeter 1974; Kwok 1975), internal holes in H II regions (e.g., Krishna Swamy and O'Dell 1967; Mathews 1967; Cochran and Ostriker 1977), ionized features such as the Barnard Loop (e.g., O'Dell, York, and Henize 1967), and even large-scale interstellar structures (e.g., Elmegreen and Chiang 1982).

The overall effect of radiation pressure on the existing interstellar phases also depends on the gas-grain coupling. For regions in which the hotter and rarefied phases dominate, grains can drift through the gas along the *B*-field lines and will tend to diffuse out of the region (e.g., Chiao and Wickramasinghe 1972). In the denser and cooler phases where dust particles can be stopped by drag, the final results depend on the gas column density and radiation field. Massive molecular clouds are not affected by the momentum transfer from the general radiation field, but small diffuse clouds can receive a net acceleration. If one considers that the interstellar gas is distributed in clouds with a given velocity dispersion in the *z*-direction, a fraction of these clouds can be raised above the main gaseous disk by radiation pressure of starlight. This "photolevitation" effect, which is the subject of this paper, is effective only in small semiopaque clouds. Here we show that the process can maintain a neutral gas column density of about 10^{20} cm^{-2} at high latitudes. The paper is organized as follows. Section II discusses the relevant features of radiation pressure and gas-dust coupling in diffuse clouds. The general formulation for photolevitation and its application to the solar circle are presented in § III. A brief discussion of possible implications is given in § IV.

[1] Instituto de Astronomía-UNAM, México.
[2] Max Planck Institut für Astrophysik, F.R.G.
[3] Dipartimento di Fisica, Sezione di Astronomia, Pisa.
[4] Dipartimento di Astronomia, Firenze.

II. RADIATION PRESSURE

a) Effects on a Dusty Cloud

Consider an external radiation energy flux, $F = \int F_\lambda d\lambda$, entering at one face of a dusty interstellar cloud. The flux is absorbed and scattered as the photons penetrate through the cloud and, for a constant dust-to-gas ratio, the dust optical depth can be written as

$$\tau = \sigma_d N , \tag{1}$$

where σ_d is the optical dust cross section per gas particle, and N is the total gas column density (atomic plus molecular). The cross section per gas particle, aside from the dust-to-gas ratio, depends on the average optical properties of interstellar grains. These, in turn, depend on their size distribution (e.g., Mathis, Rumpl, and Nordsiek 1977; Greenberg and Chlewicki 1983) and assumed grain composition (e.g., Draine and Lee 1984). For a cloud with cosmic abundances and a "normal" dust-to-gas ratio, however, a simple and useful approximation to the minimum total gas column density at $\tau = 1$ in the visible can be expressed as (Franco and Cox 1986)

$$N_\tau \simeq 5 \times 10^{20}\left(\frac{a}{10^{-5}\ \mathrm{cm}}\right)\left(\frac{\rho_d}{2\ \mathrm{g\ cm^{-3}}}\right)\ \mathrm{cm^{-2}} , \tag{2}$$

where a is the grain radius, and ρ_d is the mass density in a dust particle. This value, which is used as a rough estimator of the involved column densities, is similar to the one derived from interstellar reddening by Jura (1975) and corresponds to a normal interstellar extinction of about $A_V \simeq 0.3$ (e.g., Savage and Mathis 1979).

The resulting radiation pressure on dust grains located at an optical depth τ from the cloud edge is

$$P(\tau) = \frac{Q_p F e^{-\tau}}{c} , \quad (3)$$

where $Q_p F = \int Q_p(\lambda) F_\lambda \, d\lambda$ is the "effective" flux for radiation pressure, $Q_p(\lambda)$ is the efficiency factor for radiation pressure [its average value is $Q_p = F^{-1} \int Q_p(\lambda) F_\lambda \, d\lambda$], and c is the speed of light. Grains located at $\tau \geq 1$ do not feel any substantial pressure and, thus, the effectiveness of the momentum transfer from the photon field is restricted to regions with moderate column density values, say, of about a few times 10^{20} cm^{-2}. The effective flux integral, $\int F_\lambda Q_p(\lambda) d\lambda$, depends on the details of the ambient radiation field and the type of grain selected as representative of the grain population. Figure 1 shows its values, as a function of wavelength, for spherical graphite and "astronomical silicate" grains with radius $a = 10^{-5}$ cm (e.g., Draine and Lee 1984; Draine 1987; see also van de Hulst 1957; and Wickramasinghe 1973), and the mean interstellar radiation field near the Sun (we have assumed $F_\lambda = 2\pi J_\lambda$, where $4\pi J_\lambda$ is the average intensity of the radiation field given by Mathis, Mezger, and Panagia 1983). This figure illustrates the difference in response from different dust components and provides a quantitative estimate of the effects in the solar neighborhood. The efficiency factors have their maximum values at about $\lambda \sim 2000$ Å for silicates and $\lambda \sim 5000$ Å for graphite, but a substantial contribution to the pressure is achieved up to wavelengths of about 1.5 μm. The particular values for the maximum wavelength contributing to the pressure, however, depend on the type of cloud considered and the asymmetries of the ambient radiation field. For clouds that are opaque at $\lambda \sim 1.5$ μm, the grain population located near the edges can receive, depending on composition, effective fluxes ranging between 5×10^{-3} and 1.5×10^{-2} ergs cm^{-2} s^{-1}. A rough approximation to the average effective flux for a mixture of silicates and graphite, then, is $\sim 10^{-2}$ ergs cm^{-2} s^{-1}. If one considers semiopaque clouds (i.e., transparent in the near-infrared) and immersed in the disk (i.e., receiving an isotropic radiation bath), the maximum wavelength participating in the net momentum transfer has to be reduced to values in the optical range (i.e., about ~ 5500 Å) and the effective flux is reduced accordingly (i.e., decreases to values between 4×10^{-3} to 7×10^{-3} ergs cm^{-2} s^{-1} for $\lambda \sim 5500$ Å). When the radiation field is anisotropic, as in clouds located near stellar clusters or at high latitudes, the full spectral interval up to 1.5 μm has to be considered.

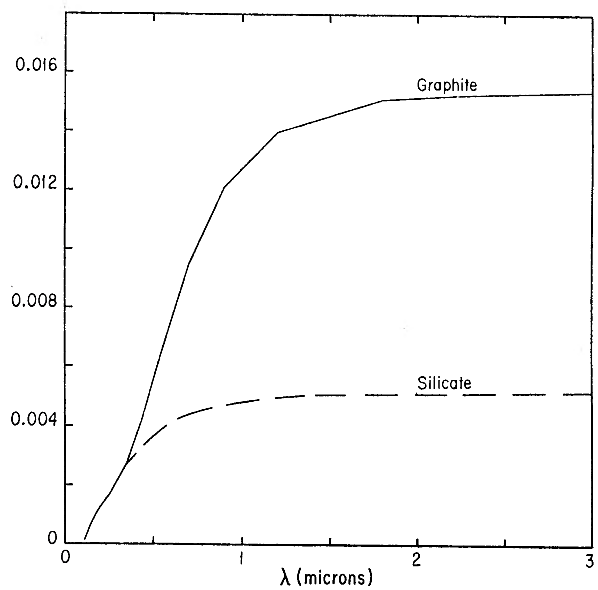

FIG. 1.—The "effective" flux for radiation pressure at the solar neighborhood for two types of spherical grains with $a = 10^{-5}$ cm. The radiation field is from Mathis, Mezger, and Panagia (1983) and the grain data from Draine and Lee (1984) and Draine (1987). The solid line corresponds to randomly oriented graphite and the dashed line to "astronomical silicates."

The extent to which this radiation pressure can be transmitted to the gas depends, of course, on the dust-gas coupling. For charged dust particles, with electrostatic potential U and moving with velocity v_d through a partially ionized medium, the mean free path for stopping a grain via electric and viscous interactions with gas particles is (e.g., Draine and Salpeter 1979)

$$\lambda_c \simeq \frac{1}{n\mu} \left(\frac{m_d}{A} \right) f(s) , \quad (4a)$$

with

$$f(s) = \frac{3\pi^{1/2} s}{8 \Sigma_j g_i} , \quad (4b)$$

$$g_j = \left(\frac{m_j}{\mu} \right)^{1/2} \left(\frac{n_j}{n} \right) \left(1 + \frac{9\pi}{64} s_j^2 \right)^{1/2} \times \left[1 + \frac{3\pi^{1/2} \phi^2 \ln(\Lambda)}{8(s_j^3 + 3\pi^{1/2}/4)(1 + 9\pi s_j^2/64)^{1/2}} \right] , \quad (4c)$$

and

$$s = \left(\frac{\mu v_d^2}{2kT} \right)^{1/2} , \quad s_j = s \left(\frac{m_j}{\mu} \right)^{1/2} , \quad (4d)$$

$$\phi = \frac{eU}{kT} , \quad \Lambda = \frac{3}{2ae\phi} \left(\frac{kT}{\pi x n} \right)^{1/2} , \quad (4e)$$

where e is the unit charge, n is the total gas density, m_j and n_j are the mass and density of ion species j, x is the ionization fraction, μ is the mean mass per gas particle, m_d is the mass of the dust grain, and A is the geometrical cross section of the grain. The values for the dust mass and geometrical cross section depend on the assumed grain geometry but their ratio, $m_d/A \simeq 1.5a\rho_d$, is almost independent of this geometry.

The function $f(s)$ is bounded between 0 and 1, and the terms g_j include the viscous and Coulomb drags. Aside from protons, the most abundant ion providing the Coulomb drag in H I clouds is C^+. For $n_{C^+}/n = 10^{-4}$ (and assuming a grain potential $U = -0.5$ V and $T = 80$ K), Figure 2 shows the variations of $f(s)$ with the ionization fraction, x (the curve with $x = 10^{-4}$ corresponds to pure C^+ drag). For slowly moving grains ($s \leq 1$), which is the likely case in diffuse clouds (e.g., Chiao and Wickramasinghe 1972), the value of $f(s)$ is well below unity. The least favorable case for the coupling results when $f(s) = 1$ (i.e., fast grains) and the corresponding maximum gas column density (assuming cosmic abundances) is

$$N_{\max} = n\lambda_{\max} \simeq 10^{19} \left(\frac{a}{10^{-5} \text{ cm}} \right) \left(\frac{\rho_d}{2 \text{ g cm}^{-3}} \right) \text{cm}^{-2} , \quad (5)$$

which is about 50 times smaller than the minimum value defined for $\tau = 1$. Thus, even in this unfavorable case the gas

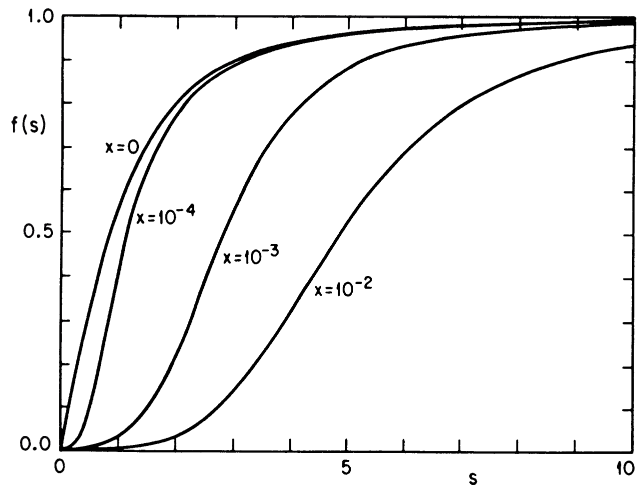

FIG. 2.—Variation of $f(s)$ with the ionization fraction, x, in diffuse clouds. The assumed grain electrostatic potential is $U = -0.5$ V and the gas temperature is $T = 80$ K. Curves with $x \geq 10^{-4}$ were computed with $n_{C^+}/n = 10^{-4}$.

shares the effects of the radiation pressure at about the same moderate values of the opacity where the dust grains receive most of their momentum gain.

Clouds with column densities in excess of the stopping column density (i.e., any "standard" diffuse cloud) and immersed in an isotropic radiation bath receive an effective confining pressure

$$\int_0^{\tau_c} P(\tau) d\tau \simeq \frac{FQ_p}{c} (1 - e^{-\tau_c}) , \quad (6)$$

where τ_c is the total optical depth of the cloud. The importance of this pressure in the overall cloud structure, however, depends on the ratio of the radiation energy density to the external ambient pressure. From Figure 1, taking a value intermediate to the ones of silicate and graphite at $\lambda \sim 5500$ Å, semiopaque clouds in the solar neighborhood can receive an effective flux of about $(FQ_p)_\odot \sim 5 \times 10^{-3}$ ergs cm^{-2} s^{-1}, which translates into a pressure of about $P_\odot \sim 1.7 \times 10^{-13}$ dyn cm^{-2}. This value is about half of the one derived from the diffuse cloud data (e.g., Spitzer 1978) and indicates that radiation could play a significant role in the structure of these clouds.

When the photon field is anisotropic, on the other hand, the cloud receives a net acceleration. Clouds located in the neighborhood of star clusters are accelerated away from the cluster (e.g., Mathews 1967; Krishna Swamy and O'Dell 1967; O'Dell *et al.* 1967; Elmegreen and Chiang 1982), and clouds located above midplane can be pushed by the radiation field from the disk to even larger heights. In this latter case, which is the one explored in this paper, the clouds are flattened during the acceleration process and can be ejected from the disk. The sputtering time scales for grains drifting with $s \leq 5$ under diffuse cloud conditions is well in excess of 6×10^9 yr (e.g., Draine and Salpeter 1979), indicating that grains can survive a wide range of radiative forces and are not destroyed during cloud acceleration.

b) The Average Radiative Flux in a Disk Galaxy

The radiation energy density in disk galaxies decreases exponentially with galactocentric distance (e.g., van der Kruit 1986). The variation in the z-direction, on the other hand, follows the vertical distribution of the stars providing most of the radiative energy. The bulk disk population can be represented by a sech^2 (z/H) distribution (e.g., van der Kruit and Searle 1981), corresponding to an isothermal self-gravitating fluid with scale height H, whereas the younger stellar populations may be better described by an exponential or a Gaussian distribution. The relative importance of the flux provided by each one of these two populations varies from place to place in the Galaxy. For simplicity, we assume that both components contribute to a smooth average flux with an average *optical* scale height H_*. The total average power unit area emitted by each face of the galaxy will be denoted F_t. Any increase over this average F_t, supplied by nearby stellar clusters, is considered in a separate manner.

Let $F_{\rm down}$ be the average energy flux passing through a point located at a height z from the plane and directed toward midplane, and $F_{\rm up}$ the corresponding one directed outward the disk (i.e., $F_t = F_{\rm up} + F_{\rm down}$). Their ratio provides a simple diagnostic for the bulk effects of the radiation field

$$\gamma(r) = \frac{F_{\rm down}}{F_{\rm up}} = \frac{\int_z^\infty F(z)dz}{\int_{-\infty}^z F(z)dz} = \frac{1 - W(r)}{b + W(r)} , \quad (7)$$

where $r = z/H_*$, b is a constant depending on the average extinction of the disk, and $W(r)$ is tanh (r) or erf (r) for the sech^2 or Gaussian distributions, respectively. For $\gamma(r) \geq 1$ the clouds receive partial confinement toward the disk but for $\gamma(r) < 1$ the pressure from the average photon field will tend to "levitate" the clouds out of the disk.

The values of b range from 1 (in the transparent disk case) to 0 (when the central regions of the disk are completely opaque). For $b = \frac{2}{3}$, corresponding to a semitransparent case in which one-third of the light from below midplane is absorbed, the position for $\gamma = 1$ corresponds to $z/H_* \simeq 0.17$ and 0.15 for the sech^2 and Gaussian distributions, respectively (i.e., if $H_* \simeq 150$ pc, clouds can be levitated when located above $z \simeq 25$ pc). For $b = 1$, on the other hand, the lifting process is effective from any location above midplane.

The variation of $F_t = \int 2\pi J_\lambda d\lambda$ with Galactocentric radius for the Milky Way is given by Mathis, Mezger, and Panagia (1983). The spectral form of the radiation field is roughly similar at different radii and, at least at short wavelengths, is also similar to those observed in other spiral galaxies (i.e., Witt and Johnson 1973). The main contribution at wavelengths below 3000 Å and beyond 1 μm comes from early-type stars and from red giants, respectively. These stellar components are confined to a Gaussian disk with $H_* \sim 50$ pc (see also Blaauw 1965; Chiao and Wickramasinghe 1972). At intermediate wavelengths, however, the stellar components have scale heights between 190 and 270 pc. For simplicity, then, one can assume an average optical height of about 150 pc for our Galaxy.

III. PHOTOLEVITATION

a) The Equation of Motion

The gravitational acceleration in the z-direction of an isothermal self-gravitating disk with *mass* scale height H_M can be written as

$$g_z = \beta \tanh (z/H_M) , \quad (8)$$

where $\beta = 4\pi G H_M \rho(0)$, G is the gravitational constant, and $\rho(0)$ is the total mass density at midplane. Real galaxies have several mass components and g_z could have a more complex functional form. A recent derivation of the acceleration in the solar neighborhood (Kuijken and Gilmore 1989), however, can be approximated (within 20%) up to about 1 kpc from mid-plane by equation (8) with the values $\beta_\odot \simeq 5.8 \times 10^{-9}$ cm s^{-2} and $H_\odot \simeq 300$ pc.

The total outward radiation pressure felt by a cloud at a given location can be written as the sum of contributions from the average field and from nearby stellar clusters

$$P_{\rm rad} = P_{\rm av} + P_{\rm cl} , \tag{9a}$$

with

$$P_{\rm av} = \frac{Q_p(F_{\rm up} - F_{\rm down})}{c}(1 - e^{-\tau_c}) = \frac{Q_p F_t}{c}(1 - e^{-\tau_c})\left[\frac{1-\gamma(z)}{1+\gamma(z)}\right] , \tag{9b}$$

and

$$P_{\rm cl} = \frac{Q_p L(1 - e^{-\tau_c})}{4\pi z^2 c} , \tag{9c}$$

where $F_t = F_{\rm up} + F_{\rm down}$ is the total power per unit surface from one face of the disk, and LQ_p is the effective luminosity of the nearby cluster.

Aside from the gravitational and radiation fields, the cloud motion can also be influenced by the presence of Galactic *B*-fields and the drag from the ambient medium. The role played by a magnetic field depends of course on the field configuration, and it could be very important when oriented parallel to the plane (e.g., Elmegreen 1981). This configuration, if anchored to the central parts of the disk, provides a magnetic tension which will increase the downward force, lowering the levitation height (B. Elmegreen, personal communication). The orientation of the large-scale Galactic field is predominantly parallel to the plane but has random fluctuations, with strengths similar to the one of the average field at almost any scale (e.g., Serkowski 1962; Mathewson and Ford 1970; Vrba, Strom, and Strom 1976). Thus, a good fraction of clouds can leak out through the available open channels and, for simplicity, we will neglect magnetic fields.

The equation of motion for the center of mass of a dusty cloud in the *z*-direction, including the drag exerted by an ambient medium with sound speed c_s, is

$$\dot{v}_z = \frac{P_{\rm rad}}{N\mu} - \beta \tanh(y) - \frac{n_a(z)}{N} U_z , \tag{10}$$

where N is now the cloud total column density along the *z*-axis, $n_a(z)$ is the density distribution of the ambient gas, y is defined as z/H_M, and U_z is a function depending on the cloud shape and velocity. For subsonic motions with laminar streamlines flowing around the cloud, U_z can be approximated by $c_s v_z$ (we thank the referee for pointing this out). Otherwise, for supersonic motions or turbulent flows, it may be better approximated by v_z^2. Equation (10) neglects compressions and assumes that the cloud as a whole receives the effects of $P_{\rm rad}$ and the drag. In reality, $P_{\rm rad}$ operates up to column densities with $\tau_c \sim 1$ and the drag compresses only the outer layers (driving sonic waves inward which eventually reduce v_z). Hence, both processes will tend to level the cloud to lower column densities (i.e., N is reduced while the cloud area is increased during the evolution). For simplicity N is assumed constant during the evolution and the range of validity of this approximation is discussed below.

Defining v_0 as the initial cloud velocity in the *z*-direction, the formal solution to equation (10) in the hypersonic or turbulent regimes is

$$v_z = e^{-D}\left\{v_0^2 - 2\int_0^z \left[\beta \tanh\left(\frac{z}{H}\right) - \frac{P_{\rm rad}}{N\mu}\right] e^{2D} dz\right\}^{1/2} , \tag{11}$$

with the drag term

$$D = \int_0^z \frac{n_a(z)}{N}\, dz .$$

This equation has no analytical solutions but, selecting the stratification for $n_a(z)$, can be easily solved numerically. For large values of the drag integral (i.e., $D > 0.5$), the assumption that N remains constant is no longer valid. For moderate values of the drag (i.e., when $D \sim 0$ for most of the evolution), the maximum height reached by a cloud, $y_m = z_m/H_M$, is independent of the choice of U_z and is defined by

$$\beta H \ln[\cosh(y_m)] = \frac{1}{2}v_0^2 + \frac{F_t Q_p H_M y_m (1 - e^{-\tau_c})}{cN\mu}\left\langle\frac{1-\gamma}{1+\gamma}\right\rangle + \frac{LQ_p(1 - e^{-\tau_c})}{4\pi c N\mu}(z_0^{-1} - z_m^{-1}) , \tag{12}$$

where z_0 is the initial cloud distance to the cluster, and the symbol $\langle\,\rangle$ represents the mean value over the cloud path. The left-hand side of equation (12) is the gravitational term, and the right-hand side, the "cloud" term, contains all the cloud properties and the radiation field information.

The intercloud medium (which is the main contributor to the drag inside the disk) has densities between 0.1 and 0.01 cm^{-3}, and the flattening associated to the drag inside the disk becomes important in clouds with column densities of the order of $\sim 10^{19}$ cm^{-2}. This imposes a constraint to the constant N approximation and equation (12) is valid only for N larger than several times 10^{19} cm^{-2}. The value of $P_{\rm rad}$, on the other hand, decreases fast for column densities above the one defined in equation (2), $N_\tau \simeq 5 \times 10^{20}$ cm^{-2}. Clouds with larger column densities are not evenly accelerated and are eventually flattened down to $\sim N_\tau$ during their evolution (for intense radiative fields they can even be fragmented by Rayleigh-Taylor instabilities). Thus, when $\tau_c > 1$, the photon field adjusts the cloud optical depth to be of order unity at the most. This self-regulatory action of the photolevitation process provides one simplification to the problem. Given that $\int_0^1 x^{-1}(1 - e^{-x})dx \simeq 0.8$, for a "normal" dust-to-gas ratio, the quantity

$$\frac{(1 - e^{-\tau_c})}{cN\mu} = \frac{\sigma_d}{c\mu}\frac{(1 - e^{-\tau_c})}{\tau_c} \simeq 2.4 \times 10^{-8} \tag{13}$$

can be taken as a constant (its value, however, increases linearly with an increasing dust-to-gas ratio). In summary, all the approximations are valid for N of the order of 10^{20} cm^{-2}.

The mean value $\langle(1-\gamma)/(1+\gamma)\rangle$ can be solved analytically for the cases discussed in § II*b*

$$\left\langle\frac{1-\gamma}{1+\gamma}\right\rangle = \frac{H_*}{z_m}\int_0^{z_m/H_*}\frac{1-\gamma(r)}{1+\gamma(r)}\,dr = \left(\frac{b-1}{b+1}\right) + \left(\frac{2}{b+1}\right)\frac{H_*}{z_m}\int_0^{z_m/H_*} W(r)dr , \tag{14a}$$

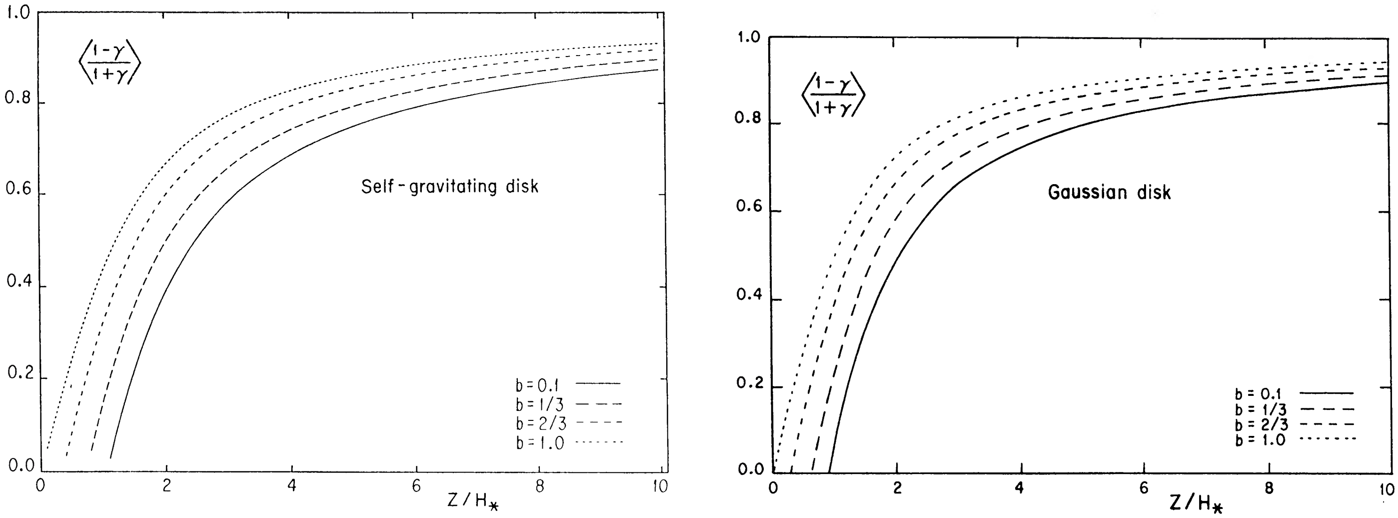

FIG. 3a FIG. 3b

FIG. 3.—Mean value of the average radiation field as a function of the maximum cloud height, $\langle(1-\gamma)/(1+\gamma)\rangle$, for different values of the opacity parameter, b. (a) Self-gravitating disk. (b) Gaussian disk.

where H_* is the *optical* scale height (which is usually smaller than the *mass* scale height, H_M), and the integral is equal to

$$\int_0^{z_m/H_*} W(r)dr = \ln[\cosh(z_m/H_*)]\ , \quad (14b)$$

for the self-gravitating disk, or

$$\int_0^{z_m/H_*} W(r)dr = \frac{z_m}{H_*}\operatorname{erf}\left(\frac{z_m}{H_*}\right) + \pi^{-1/2}[e^{-(z_m/H_*)^2} - 1]\ , \quad (14c)$$

for the Gaussian disk. Figures 3a and 3b display equation (14) for both disk stratifications and several values of b.

b) Graphical Solution

The initial velocity, v_0, and the cluster contribution to the radiative flux can be gathered together to define an "effective" velocity

$$v_{\rm eff} = \left[v_0^2 + \frac{LQ_p(1-e^{-\tau_c})}{2\pi cN\mu z_0}\right]^{1/2} \simeq 10\left[v_6^2 + 1.5\frac{L_6}{z_{19}}\right]^{1/2} \text{km s}^{-1}\ , \quad (15)$$

where $v_6 = v_0/10$ km s^{-1}, $L_6 = LQ_p/10^6\ L_\odot$, and $z_{19} = z_0/10^{19}$ cm. Using $\beta_\odot$ and $H_\odot$ to illustrate the effects in the solar circle, the solution for the maximum height (eq. 12) can be written as

$$\ln\left[\cosh\left(\frac{z_m}{300\text{ pc}}\right)\right] \simeq 9.7\times10^{-2} \times\left[\left(\frac{v_{\rm eff}}{10\text{ km s}^{-1}}\right)^2 - 0.43\left\langle\frac{1-\gamma}{1+\gamma}\right\rangle\left(\frac{z_m}{H_\odot}\right)R\right]\ , \quad (16)$$

with

$$R = \left(\frac{F_t Q_p}{10^{-2}\text{ ergs cm}^{-2}\text{ s}^{-1}}\right)\ . \quad (17)$$

Figures 4a and 4b show the solutions to equation (16), as intersections of the gravitational term with the cloud term, for different values of R. Two cases for the effective velocity, 8 km s^{-1} (the velocity dispersion for the "normal" population of diffuse clouds; e.g., Kulkarni and Fich 1985) and 15 km s^{-1} (the effective velocity reached near a stellar cluster with $L_6 = 1$), are shown in the figures. For $v_{\rm eff} = 8$ km s^{-1} (Fig. 4a), the maximum height with $R = 0$ is $z_m = 100$ pc and increasing values in R result in increasing maximum heights, reaching about 1 kpc for $R \simeq 20$. For $v_{\rm eff} = 15$ km s^{-1} (Fig. 4b), the solutions follow the same trends but now they are shifted to larger values (i.e., $z_m = 200$ pc for $R = 0$).

In the absence of radiation forces, the maximum cloud height for $v_{\rm eff} = 8$ km s^{-1} corresponds to the usual scale height of the H I cloud component, ~100 pc (e.g., Baker and Burton 1975). The value of R in the local vicinity of the Sun ranges from ~0.5 to about 1 and, except for locations in the neighborhood of nearby clusters, the effect in normal clouds increases this maximum height by 10%–20%. Clouds with higher than normal dust-to-gas ratios, however, will be selectively raised to higher latitudes. The decrease of the radiation field with Galactocentric distance indicates that the process is not operative in the outer Galaxy but should be important in the inner parts. In particular, the effective velocity and R can reach large values in sites with intense star formation and in spiral arms. These active regions, then, can be very efficient in driving diffuse clouds into the base of the halo. Similarly, the process should be very important in starburst galaxies and active galactic nuclei.

IV. DISCUSSION

Radiation pressure on dust grains may play an important role in determining some features of the interstellar medium. In particular, small dusty clouds with $N < 5\times10^{20}$ cm^{-2} can be raised to considerable heights above the Galactic plane and would be observed as small local features emerging out of the disk. Some of these clouds might have a substantial fraction of molecules and could be detected in molecular emission. Depending on the radiation field and dust-to-gas ratio, these features can be cast into the halo. The overall mass flux has to be modest, but the photolevitation process can maintain a *neutral* gas column density of the order of 10^{20} cm^{-2} above the main gaseous scale height. Such a value is certainly similar to the one observed at high latitudes in the direction of the inner Galaxy (Lockman 1984), and toward large-z stars (see Edgar

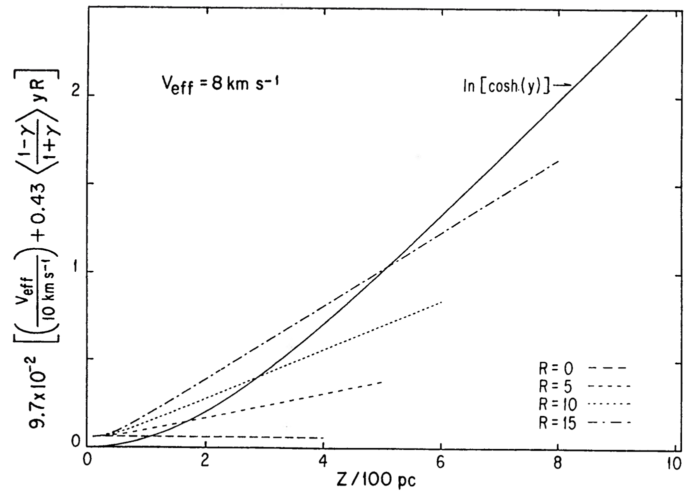

FIG. 4*a*

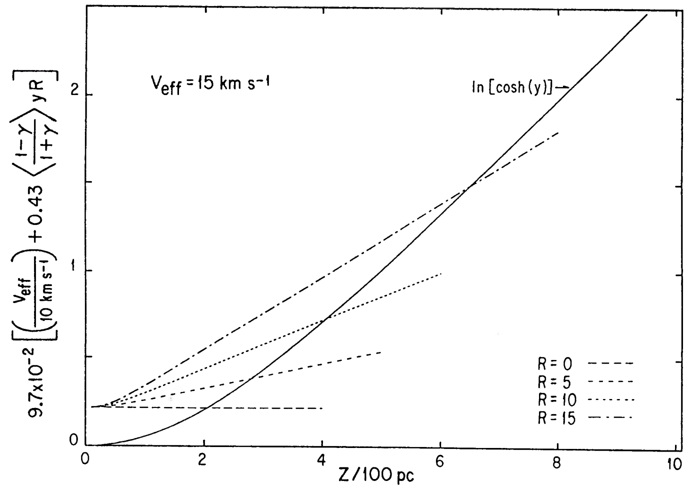

FIG. 4*b*

FIG. 4.—Graphical solution of eq. (16). The thick solid line is the gravitational term, ln [cosh (y)]. The dashed lines are the "cloud" terms for different values of $R = (F_t Q_p/10^{-2}$ ergs cm^{-2} s^{-1}), and the Gaussian light distribution with $b = \frac{2}{3}$ and $H_* = 150$ pc. (*a*) Case with $v_{eff} = 8$ km s^{-1}. For R equal to 0, 5, 10, and 15, the maximum heights are 100, 170, 290, and 510 pc, respectively. (*b*) Case with $v_{eff} = 15$ km s^{-1}. For R equal to 0, 5, 10, and 15, the maximum heights are 200, 280, 410, and 650 pc, respectively.

and Savage 1989, and references therein). Also, the collection of photolevitated clouds can resemble a gas component with higher than normal velocity dispersion and may be associated with the "fast" population of diffuse clouds discussed by Kulkarni and Fich (1985).

These effects reinforce the concept of galactic "fountains," but indicate that gas circulation may occur at least at two different levels: a "lower" and soft fountain driven by radiation pressure, and an "upper" one driven by energetic events (e.g., Shapiro and Field 1976; Bregman 1980; Cox 1981; Corbelli and Salpeter 1988; Tenorio-Tagle and Bodenheimer 1988; Houck and Bregman 1990). The physical properties of these two types of fountains are clearly different. The upper one is composed of hot and highly ionized coronal gas which would tend to fill the whole volume of the halo. The soft one is composed of dust-rich neutral clouds which would simply tend to reach equilibrium with the coronal gas and the local radiation field. Strong radiative accelerations, however, can be expected in starburst galaxies and active galactic nuclei.

Some observational evidence for the presence of dust mixed with gas at high latitudes in the Milky Way may be explained by this model. The evidence includes the extinction of high-z stars (e.g., Edgar and Savage 1989), the well-known infrared cirrus (e.g., Hauser 1988; Désert, Bazell, and Boulanger 1988), the collection of small molecular clouds reported by Magnani, Blitz, and Mundy (1985), and the Draco nebula (a high-latitude reflection nebula associated with molecular and high-velocity gas; e.g., Kalberla, Herbstmeier, and Mebold 1984; Rohlfs *et al.* 1989). The process could also be useful in understanding some observed features in external galaxies. From an analysis of the photographs of the Hubble Atlas of Galaxies, Sofue (1987) reported the presence of vertical filamentary structures of dust. These filaments have their roots in the molecular ring of the spiral galaxies NGC 253 and NGC 7331 and they extend into the halo to about 1.5–2.0 kpc, with a typical width of 50–100 pc. Another well-known example for dust at high latitudes is in M82 (Abadi and Bohren 1977; Solinger, Morrison, and Markert 1977; Telesco, Decher, and Joy 1989) which shows an extensive halo of filaments. Dust lying outside the plane (and obscuring the arm) of the spiral galaxy NGC 1808 has also been reported by Veron-Cetty and Veron (1985). Similarly, dust filaments which seem to be located above the disk of M81 can be appreciated in optical photographs (M. Peimbert, personal communication).

The details of the cloud response to strong radiation fields at large opacities was not explored here, but cloud stability cannot be granted under these circumstances (e.g., Mathews and Blumenthal 1977). If instabilities appear, the cloud is fragmented into cometary-like pieces with dense heads and floating tails (we thank B. Elmegreen for pointing this out), and may resemble the cometary structures described by Odenwald (1988). Grain drift inside the accelerated clouds was also not explored, but a certain drift may be expected. If this is the case, some grains can leave the cloud and will continue their evolution in a rarefied hot medium with a much lower drag. These bare grains are easily accelerated to very high latitudes and can even be expelled out of the galaxy (e.g., Chiao and Wickramasinghe 1972; Barsella *et al.* 1989; Ferrara *et al.* 1989). Alternatively, if sputtering is important, the grains will be destroyed somewhere in their evolution through the halo (Ferrara *et al.* 1989). Similar results are expected if the original clouds evaporate as they evolve through the coronal gas. In both cases, however, the grains will act as chemical pollutants of the halo or the intergalactic medium. These processes could explain the large scale heights found for highly refractory elements at low-ionization stages (e.g., Edgar and Savage 1989). Moreover, such a possible connection between disk and halo may be relevent in the chemical evolution of the interstellar and intergalactic medium.

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BRUNO BARSELLA and FEDERICO FERRINI: Istituto di Astronomia, Università di Pisa, Piazza Torricelli 2, 56100 Pisa, Italia

ANDREA FERRARA: Dipartimento di Astronomia, Università di Firenze, Largo E. Fermi, 50125 Firenze, Italia

JOSÉ FRANCO: Instituto de Astronomía-UNAM, Apdo. Postal 70-264, 04510 México D. F., México