GRAIN EVOLUTION IN THE FRAMEWORK OF DISK–HALO INTERACTIONS

F. FERRINI
Dipartimento di Fisica
Università di Pisa
56100 Pisa, Italy

ABSTRACT.
The presence of dust grains at high galactic latitude as well as in the Halo of external galaxies has received substantial observative support in the last few years. Besides intense hydrodynamics stirring phenomena, like Supernovae expanding shells, stellar winds and Galactic fountains, the removal of dust from the Disk can be ascribed to the global galactic radiation field. The continuous sputtering in the hot Halo gas may explain the large scale height found for refractory elements (Edgar and Savage, 1989).

1. GRAINS AT HIGH GALACTIC LATITUDES.

Dust is now recognized to be a fundamental component of the galaxy on all length scales; from local dense clouds to molecular cloud concentrations, accompanying OB associations to fully global distributions. Indeed the IRAS observations at 100 μm revealed that, in the Milky Way, dust is distributed similarly to the HI component (Burton, 1990). The presence of grains is not limited to the Disk but dust is pervasive also at high galactic latitudes, as it results evident from the extended search by Désert *et al.* (1988) for clouds with enhanced infrared emission with respect to the normal population of diffuse clouds. Isolated dust clouds have been studied in detail by Rohlfs *et al.* (1989) and Herter *et al.* (1990).

Clear views of the large scale distribution of gas and dust out of the Disk have been obtained for external galaxies. Véron–Cetty and Véron (1985) dividing a blue image by an infrared image of NGC 1808, noticed that the bright central nucleus is embedded in a filamentary reddish structure, obscuring the arm. Sofue (1987), from an analysis of the photographs of the Hubble Atlas of Galaxies reported the presence of dark filaments vertically emerging toward the Halo from the 3–4 kpc molecular ring in NGC 253 and NGC 7331, up to 1–2 kpc on the Disk plane. Similarly, Rand *et al.* (1990) have revealed numerous faint vertical filaments

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extending up to $\sim$ 2 kpc off the plane of the edge–on spiral NGC 891 (see also Allen and Dettmar, this Conference).

Furthermore, intergalactic extinction, due to both a diffuse medium and individual clouds (Rudnicki *et al.* 1989) is a subject of renewed interest, because of its connection with cosmological observations and theories.

The frequence of dusty clouds out of the Disk suggests that they are rather resistant to the violent phenomena which are responsible for a removal of material from the Disk, or that a soft fountain is connected with their presence. Furthermore, the fate of naked grains in the Halo ambient deserves investigation.

2. FORCES ON GRAINS.

The dynamical evolution of small solid particles in interstellar space has been studied, beginning with some pioneering works in the 30's (see Spitzer 1941 and references therein), under a variety of different conditions. Aside from the intensity of the radiation field, a key parameter for 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 grain–gas interactions are sensitive functions of the gas density and grain charge. If gas drag is neglegible, 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 1972). This process seems to be the driving agent of massive winds from cool giant stars (*e.g.* Salpeter 1974; Kwok 1975), internal holes in HII regions (*e.g.* Cochran and Ostriker 1977), and large scale interstellar structures such as the Barnard Loop (*e.g.* O'Dell *et al.* 1967).

2.1 Early Studies on Dust Motion.

Only two papers by Pecker (1972, 1974) and one paper by Chiao and Wickramasinghe (1972) have taken up large scale dust motion. In all cases particle motions are considered far enough from stars to disregard any local effect (winds, etc.). Pecker (1972) considered, at first, the effect of individual stars of various spectral types on grains, ranging from 10^{-3} to 10 μm, varying the star spectral type (and consequently their effective temperature). The optical properties of the grains, that is their radiation pressure coefficient Q_{pr}, were considered in a rather qualitative way.

He concluded that grain size plays a larger role than its composition, resulting in a particularly efficient expulsion for grains with radii $\simeq 0.1$ μm; the early type stars (O5) can efficiently expel any grain. Similar results have been obtained by Divari and Reznova (1970).

The subsequent step in Pecker's calculation was the evaluation of the forces exercised by a 'synthetic' galaxy on dust particles. His model takes into account, schematically at least, the presence of "invisible matter" in the Disk as well as a distribution of visible matter and light in the Disk.

The result is a generalized attraction of dust grains, but this is true for very high temperatures of the stars in the Disk. Pecker thus concluded that the time variation of the ratio M/L is a fundamental factor in determining the behaviour of grains, especially as regards the early phases of evolution of our galaxy.

Chiao and Wickramasinghe (1972) studied the problem in a similar way, first in the interior of the Disk, by calculating the contributions of single stars, with gravitation and radiation forces being calculated in a simple way. In the discussion of forces inside the Disk, these authors correctly take into account the drag force due to gas clouds and the magnetic drift exerted on charged grains. They concluded that the expulsion of dust grains is very efficient for spiral galaxies.

The fact that the conclusions of these authors are opposite to each other is a clear indication that, although the physics of this problem can be formulated very simply, the end result depends critically on the adopted description both of the dust and of the galaxy properties.

2.2 Recent Studies on Dust Motion.

Our group considered recently in some more detail the problem of the motion of dust particles in the galactic radiation field (Greenberg *et al.* 1987; Ferrini *et al.* 1988; Barsella *et al.* 1989; Ferrara *et al.* 1989 and 1990). For the gravitational force the problem is extremely easy: the force on a grain of mass m_g may be written:

$$\vec{F}_G(\vec{r}) = m_g \vec{G}(\vec{r}) \tag{1}$$

where $\vec{G}(\vec{r})$ is the gravitational field intensity at the point $\vec{r}$.

The formula for the radiation pressure force is more complicated, being an integral over the radiation frequency dependent Q_{pr}:

$$\vec{F}_R(\vec{r}) = \pi a^2 \int d\vec{\rho} \int d\nu Q_{pr}(a,\nu) \vec{\Psi}(\vec{r},\vec{\rho},\nu) \tag{2}$$

$\vec{\Psi}$ is the radiation field due to the galactic element at $\vec{\rho}$ on the grain at position $\vec{r}$ at frequency ν.

The wavelength dependence of the luminosity is assumed independent of the position. Therefore, the radiation field function may be written:

$$\vec{\Psi}(\vec{r},\vec{\rho},\nu) = \vec{\Xi}(\vec{r},\vec{\rho})\Omega(\nu)$$

and the integration over ν in (2) yields the formula:

$$Q^*_{pr}(a) = \int d\nu Q_{pr}(a,\nu)\Omega(\nu) \tag{3a}$$

$$\vec{F}_R(\vec{r}) = \pi a^2 Q^*_{pr}(a) \int d\vec{\rho}\, \vec{\Xi}(\vec{r},\vec{\rho}) = \pi a^2 Q^*_{pr}(a)\vec{\Gamma}(\vec{r}) \tag{3b}$$

The expression for the radiation pressure force is reduced, therefore, to a form similar to that for the gravitational force.

The principal populations of interstellar grains may be divided optically into two categories: dielectric and metallic. The dielectric grains are represented by either silicate core–organic refractory mantles (Greenberg and Chlewicki, 1983) or by pure silicate grains (Mathis *et al.* 1977). We find convenient to use the available Draine and Lee (1984) "astronomical silicate" properties as representative of the dielectrics. Metallic grains are represented by graphite, whose optical constant are taken from Tosatti and Bassani (1970) and Phillip (1977).

A detailed knowledge of the luminosity and matter distribution of the underneath galaxy is required to compute the grain evolution. A spiral galaxy may be characterized by three components: Bulge, Disk and Halo. The Disk is modelled as an infinitely thin axially symmetric exponential distribution of luminosity and matter. The Bulge is considered as a massive and luminous addition to the center of the galactic Disk, and the Halo is considered completely dark with a spherically symmetric mass structure. We considered the detailed frequency dependence of the galactic radiative flux, $\Omega(\nu)$ different for the various Hubble types of galaxies, following Pence (1976) and Yoshii and Takahara (1988), which give the spectrum for λ between 1400 to 8000 Å.

We used as a test galaxy, NGC 3198, which is a fairly well studied Sc galaxy (Wevers 1984, Burstein and Rubin 1985, van Albada *et al.* 1985), to analize the spatial distribution of radiative and gravitational forces, considering then only the static aspect of the problem. A typical example of the fate of a grain located at the border of the Disk is shown in Fig. 1.

The main results of our analysis, extended to other 15 galaxies, for which we have good models for the luminous and matter distributions, and to an extended range of grain radii, may be briefly summarized as follows:

i) Graphite grains with radii in the 0.02–0.2 μm range are expelled from the studied galaxies.

ii) Silicate grains of intermediate radii range (0.05–0.2 μm) have, in general, equilibrium positions high on the galactic Disk, inside the mass distribution of the Halo. The equilibrium positions range from 2/10 to 8/10 of the Halo radius.

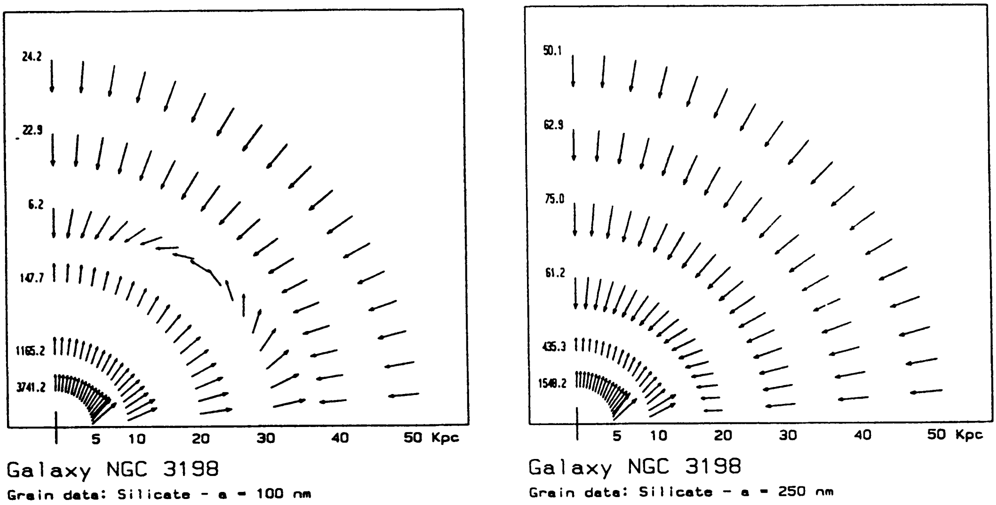

Figure 1. The distribution of total resulting force on silicate grains (radii 0.1 and 0.25 μm) in the plane perpendicular to the galactic Disk is shown for the galaxy NGC 3198. It is clear that the grain can be removed from the Halo–Disk interface; a static equilibrium position is present at an height of about 25 and 15 kpc respectively on the galactic polar axis.

3. PHOTOLEVITATION OF DIFFUSE CLOUDS.

The overall effect of radiation pressure on the existing interstellar phases 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 has been introduced by Franco *et al.* (1990).

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

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

where $Q_pF = \int Q_{pr}(\lambda) F_\lambda d\lambda$ is the "effective" flux for radiation pressure. The total confining pressure is

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

where τ_c is the total optical depth of the cloud.

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 $10^{20}\,\mathrm{cm}^{-2}$ (Franco and Cox, 1986).

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, the mean free path for stopping a grain via electric and viscous interactions with gas particles is (*e.g.* Draine and Salpeter 1979)

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

where $s = v/v_{th}$. The least favorable case for the coupling results when $f(s) = 1$ (*i.e.* fast grains) and the corresponding gas column density (assuming cosmic abundances) is

$$N = n\lambda \simeq 10^{19} \left(\frac{a}{10^{-5}\,\mathrm{cm}} \right) \left(\frac{\rho_d}{2\,\mathrm{g\,cm^{-3}}} \right) \mathrm{cm}^{-2}$$

which fixes the minimum column density for an efficient transfer of momentum from dust to gas.

Assuming the optical constant for graphite and "astronomical silicate" given by Draine (1987) and the interstellar radiation field at the solar circle given by Mathis *et al.* (1983), the effective flux results about $(FQ_p)_\odot \simeq 5 \times 10^{-3}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, which translates into a confining pressure of about $P_\odot \sim 1.7 \times 10^{-13}\,\mathrm{dyn\,cm^{-2}}$. This value is about a 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 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; 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 by Franco *et al.* , the clouds are flattened during the acceleration process and can even be ejected from the Disk. The sputtering time scales for grains drifting with $v \leq 5v_{th}$ 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.

It is easy to estimate the minimum height above which clouds can be levitated, evaluating the ratio between F_{down} the average energy flux passing through a point located at a height z from the plane and directed towards midplane, and F_{up} the corresponding one directed outwards the Disk. Adopting for the average optical scale height a value of 150 pc for a self–gravitating or gaussian Disk, diffuse semi–opaque clouds can levitate when located above $z \simeq 25$ pc.

The principal contributions to the equation of motion for the cloud are the gravitational acceleration in the z–direction and the total outward radiation pressure, due to the average field and to nearby stellar cluster: $P_{rad} = P_{av} + P_{cl}$, with

$$P_{av} = \frac{Q_p(F_{up} - F_{down})}{c}(1 - e^{-\tau_c}), \qquad P_{cl} = \frac{LQ_p(1 - e^{-\tau_c})}{4\pi z^2 c}$$

where $F_t = F_{up} + F_{down}$ is the total output per unit surface from one face of the Disk and L is the luminosity of the nearby cluster.

Franco *et al.* do not introduce the magnetic field, considering that it has random fluctuations and presents numerous open channels, and solve the equation of motion for moderate values of the drag from the ambient medium.

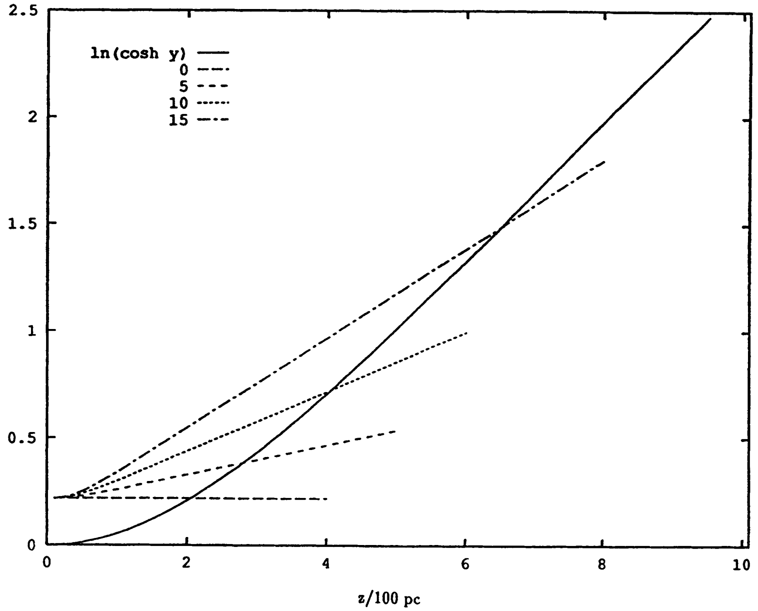

Figure 2. Graphical solution of equation of motion. The solid line is the gravitational term; the dashed lines are the radiative terms for the gaussian light distribution. For R equal to 0, 5, 10 and 15, the maximum heights are 200, 280, 410, and 650 pc, respectively.

A typical graphical solution is shown in Fig.2, where the maximum height reached by the levitated cloud is given by the intersection of the gravitational term with the radiative term for an initial cloud velocity of 15 km s^{-1} (the effective velocity near a stellar cluster with 10^6 $L_\odot$). The curves differ for the ratio of effective flux for radiation pressure to the solar circle value ($R = (F_{up} + F_{down})Q_p/5 \times 10^{-3}$ erg cm^{-2} s^{-1}). R can reach high values in sites with intense star formation and in spiral arms.

4. CONCLUSIONS.

Radiation pressure on dust grains may play an important role in determining some features of the interstellar medium. In particular, small dusty clouds with $N < 5 \times 10^{20}$ 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. Grain drift inside the accelerated clouds 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.* 1988; Ferrara *et al.* 1990).

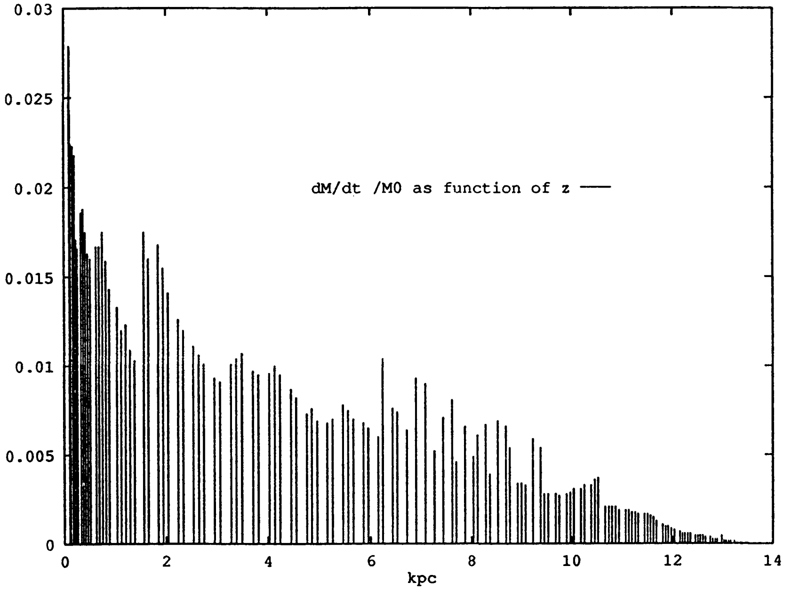

Figure 3. The fractional release of matter from a dust grain (silicate, 0.1 μm radius) moving in a hot hydrostatic isothermal (5×10^5 K) gasous Halo vs. the height on the galactic plane.

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.

In Fig. 3, I show the fraction of mass released by the grain every 10^5 yrs, as a function of the height on the galactic plane. These processes could explain the large scale heights found for highly refractory elements at low ionization stages (*e.g.* Edgar and Savage 1989 and Savage, this Conference). Moreover, such a possible connection between Disk and Halo may be relevant in the chemical evolution of the interstellar and intergalactic medium.

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