Expulsion of Dust Aggregates from Galaxies

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Abstract.

In this paper we analyse the possibility of dust being repelled away from a galactic disk by radiation pressure exerted by starlight, studying the effect of a grain aggregate model for the dust. It was found that the aggregated structure enhances the effect of radiation pressure.

1. Introduction

The possibility of dust being repelled away from a galactic disk by radiation pressure of starlight in the disk was first considered in the papers by Pecker [1] and Chiao and Wickramasinghe [2]. Greenberg et al. [3] considered the possibility of confining dust material high above the plane. In subsequent papers the model suggested in [3] was modified to include the effects of viscous forces and the effects of sputtering on the survival of dust in the halo as it moves through hot gas [4]. More recently, the ideas presented in the above papers were developed by Davies [5], using a new numerical model and adding the effects of disk opacity. The cosmological effects of dust expulsion have been treated by Aguirre et al. [6]. All the works cited above adopt “classical” spherical grains. However, homogeneous, spherical grains are no more than an useful idealization. Theoretical works and observational evidences suggest that interstellar grains, at least a great part of them, are fluffy (i.e. containing voids) aggregates of small subunits [7]. In particular, there are some evidences that in dense clouds the mean size of dust particles increases towards their innermost regions [8, 9]. There are two mechanisms which can lead to grain growth in dense regions: accretion of molecular mantles and coagulation of grains. Since, as shown by Draine [10] accretion cannot explain this growth, coagulation is considered as a more viable mechanism for an efficient modification of the dust grain mass spectrum in dense regions. The formation of these aggregates is expected as the results of low velocity collisions of small particles in dense clouds [11]. According to Wurm and Schnaiter [12], small aggregates in a limited size range serve as “a good and most natural model structure for interstellar dust particles”. Computation of the optical properties of these kind of particles requires the use of techniques that are quite different from the Mie formulas used in previous models [13, 14].

2. Dust Model

The dust model selected for this study was the simplest one possible compatible with the idea of working with a cluster of silicate and carbonaceous particles. A graphical representation of
the structure of the dust grain adopted is given in figure 1: the G and S components indicate, respectively, the carbonaceous and astronomical silicate particles. The component particles are arranged according to a regular tetrahedral morphology. The optical properties used in our computation are taken from papers by Tosatti and Bassani, Draine, Rouleau and Martin [15, 16, 17].

3. Galactic Model
In this paper we adopted the same model galaxy, NGC 3198, adopted previously in [4] to study the dynamical evolution of bulk grains: this choice was partly due to the fact that this galaxy is one of the most widely studied in the literature and partly because it was the galaxy used by most of the theoretical studies on grain evolution. The mass and luminosity data were taken from Wevers [18]. The computational model is fully described in [4].

4. The Forces on the Grain
The total force is the resultant of an attractive part coming from the gravitational attraction of stars and obscure matter in the disk, bulge and halo and a repulsive component coming from the starlight from disk and bulge. The equations used to compute the forces are given in the Appendix.

5. Results and Conclusions
We computed the total force resulting from the gravitational attraction of the galaxy and the radiation pressure from starlight for tetrahedral grains of many different morphologies. We assume that the galactic disk lies on the x-y plane. In all the following figures we plot the radial component of the total force along a line which bisects the y-z plane [4]. We plot the force (in newton) vs. the distance (in kpc) from the center of the galaxy.

The graphs referring to a single species of grains show that, apart from the case of bulk astronomical silicate, the radial force is positive, that is, it is directed outside the galaxy. Figures 2 to 7 refer to bulk graphite (fig. 2), bulk silicate (fig. 3), tetrahedral clusters with 4 graphite components (fig. 4), tetrahedral clusters with 4 silicate components (fig. 5), tetrahedral clusters
Figure 2. Bulk graphite grains of different radii.

Figure 3. Bulk silicate grains of different radii.

Figure 4. Tetrahedral clusters of 4 graphite monomers. The radii, here and hereafter, are referred to the equivalent volume sphere.

Figure 5. Tetrahedral clusters of 4 astronomical silicate monomers.

with one silicate and three graphites (fig. 6), and tetrahedral clusters with two silicates and two graphites (fig. 7).

Figure 8 provides a comparison for eight different species of grains. These grains are of about the same mass: $6 \times 10^{-15}$ g. In this figure the vertical scale is logarithmic.

The plots indicate that, in general, NGC 3198 repels the grains, and this is true for all the composite particles, including tetrahedral aggregates formed only by silicate material. This result indicates that an aggregated structure increases the radiation pressure force, although the component particles are made with dense bulk materials. In particular, the presence in the aggregate of a graphite or amorphous carbon grain greatly enhances the expulsion effect.

6. Appendices

The following are the equations [4] used to compute the steady forces on a fluffy grain outside the galactic disk (since the galactic model is cylindrically symmetrical only the $y$ and $z$ components are shown):
Figure 6. Tetrahedral clusters of 1 astronomical silicate and 3 graphite monomers.

Figure 7. Tetrahedral clusters of 2 astronomical silicate and 2 graphite monomers.

Figure 8. Comparison of different structures with a mass of about $6 \times 10^{-15}$ g.

Gravitational force

\[
F_{\text{grav},y} = -GM_{\text{grain}} \left[ \Phi \sin \theta_0 \int_0^{2\pi} d\phi \int_0^1 \sigma(\zeta R_M) \frac{\zeta d\zeta}{(\Phi^2 + \zeta^2 - 2\Phi \sin \theta_0 \cos \phi)^{3/2}} - \int_0^{2\pi} d\phi \cos \phi \int_0^1 \sigma(\zeta R_M) \frac{\zeta^2 d\zeta}{(\Phi^2 + \zeta^2 - 2\Phi \sin \theta_0 \cos \phi)^{3/2}} + M_{\text{bulge}} \sin \theta_0 + M(r) \sin \theta_0 \right] 
\]

\[
F_{\text{grav},z} = -GM_{\text{grain}} \left[ \Phi \cos \theta_0 \int_0^{2\pi} d\phi \int_0^1 \sigma(\zeta R_M) \frac{\zeta d\zeta}{(\Phi^2 + \zeta^2 - 2\Phi \sin \theta_0 \cos \phi)^{3/2}} + M_{\text{bulge}} \cos \theta_0 + M(r) \cos \theta_0 \right] 
\]
Radiation pressure force

\[
F_{\text{rad}, y} = \frac{\sigma_{\text{pr, disk}}}{c} \left[ \Delta \sin \theta_0 \int_0^{2\pi} d\phi \int_0^1 I(\xi R_L) \frac{\xi d\xi}{(\Delta^2 + \xi^2 - 2\xi \Delta \sin \theta_0 \cos \phi)^{3/2}} - \int_0^{2\pi} d\phi \cos \phi \int_0^1 I(\xi R_L) \frac{\xi^2 d\xi}{(\Delta^2 + \xi^2 - 2\xi \Phi \sin \theta_0 \cos \phi)^{3/2}} \right] + \\
+ \frac{\sigma_{\text{pr, bulge}}}{c} \frac{L_b \sin \theta_0}{4\pi r^2}
\]

\[
F_{\text{rad}, z} = \frac{\sigma_{\text{pr, disk}}}{c} \left[ \Delta \cos \theta_0 \int_0^{2\pi} d\phi \int_0^1 I(\xi R_L) \frac{\xi d\xi}{(\Delta^2 + \xi^2 - 2\xi \Phi \sin \theta_0 \cos \phi)^{3/2}} \right] + \\
+ \frac{\sigma_{\text{pr, bulge}}}{c} \frac{L_b \cos \theta_0}{4\pi r^2}
\]

where \( M_{\text{grain}} \) is the mass of the grain, \( \sigma_{\text{pr, disk}} \) and \( \sigma_{\text{pr, bulge}} \) the radiation pressure cross sections for the disk and the bulge respectively, \( \sigma_0 \) is the disk mass distribution, \( I \) is the disk luminosity distribution, \( R_M \) is the disk mass radius and \( R_L \) is the disk luminosity radius; \( \Phi = r/R_M \) and \( \Delta = r/R_L \). The \( \sigma_{\text{pr}} \) were computed in the framework of the transition matrix approach \[13\].

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