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The ISM in galactic halos structured by radiatively driven dust

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Abstract

Dust as traced by absorption in high resolution optical images of edge–on galaxies reveals a highly structured ISM with filaments, clumps, and loops. These structures often correlate with star formation activity in the underlying disk and the presence of halo gas – including cosmic rays. We consider the support of magnetic fields and radiation pressure for the stability of this halo gas. The halo gas is treated as a three–component fluid (electrons, ions and dust particles). The stellar radiation acts on the dust and generates a velocity difference between them and the plasma components, which in turn initiates a Rayleigh–Taylor type instability. This instability is studied numerically and we find that at non–linear stages magnetic arches with dust flowing up along magnetic field lines are produced much like the dust filaments mentioned above.

1 Introduction:

Amongst the various constituents of interstellar matter (ISM) in halos of galaxies dust is known to be present from its absorption characteristics (Keppel et al. 1991, Sofue et al. 1994, Howk & Savage 1999). This halo dust is not just dispersed into a diffuse medium, it rather shows a significant level of structuring into vertical filaments (NGC 891), large patches (NGC 4631), arches, loops, and bubbles (NGC 253). This morphological information and the related linear scales together with estimates on dust masses involved can be used to discuss possible mechanisms responsible for the transport of dust out of the galactic planes. This large scale transport of ISM from the disk into the halo is frequently discussed in terms of galactic fountain or chimney models (e.g., Norman & Ikeuchi 1989). Dust could also be driven out by the radiation pressure of the general interstellar radiation field (e.g., Ferrara 1998). In our study we exploit the possible influence of this radiatively driven dust coupled to the magnetic field on the structuring of the ISM. Resulting instabilities and density variations could strongly influence the propagation of cosmic rays into the halos of galaxies. Employing the test particle method we investigate the dynamics of dust grains within a magnetized halo with a developed magnetic arch. In our calculations the dust motion is determined by the interstellar radiation field and a height depending drag force.

2 Dynamics of a single grain

In a series of hydrodynamic simulations we could show that at low heights ($z < 200$ pc) where dust and gas are strongly coupled due to collisions, radiation pressure is inefficient to lift dust far from the plane. Within a one-fluid model we perturbed a halo equilibrium balancing pressure, gravitational and radiation forces by the radiation pressure of a typical OB-star association for a period of 30 Myrs. These simulations show that the system asymptotically runs into a new static equilibrium as long as the perturbation lasts and then falls back into the original state after the additional radiation field is switched off (Schröer & Shchekinov 1999). Similar calculations using a three-fluid code are in progress and first results show that species separation may occur, leading to a clumping of the dust fluid.

To get further insight on this behaviour, we now consider the dynamics of a single dust particle in a given environment, assuming in particular that it moves under external forces (gravitation, radiation, and collisional friction) along a magnetic arch of given form (thus the inverse effect of moving dust on large scale structure of the arch is neglected). Let $z_A = \phi(y)$ describe the shape of a magnetic line, we consider planar geometry with all variables independent on the x-coordinate. Then the equation of motion of a dust grain is

$$m_d \frac{d\mathbf{v}_d}{dt} = -m_d\mathbf{g}(\mathbf{r}) + \mathbf{F}_R(\mathbf{r}) - Q(v_d, \mathbf{r})\mathbf{v}_d \quad , \qquad (1)$$

with the additional constraint $z_A = \phi(y)$, here m_d is the grain mass, $\mathbf{v}_d$ its velocity, $\mathbf{g}(\mathbf{r})$ is the gravitational acceleration, $\mathbf{F}_R(\mathbf{r})$ the radiation pressure acting on dust particle, $Q(vd, \mathbf{r})$ is the efficiency of the drag force, which depends nonlinearly on relative velocity of dust and gas (see Draine & Salpeter 1979). The dependence of Q on $\mathbf{r}$ is due to the given gas density and temperature on which Q does depend. At $z < 200$ pc the free path of dust grains gets large enough and the dynamical behaviour of grains becomes now more independent on the gas and therefore share only a small fraction of momentum gained from photons with the gas. As a result, their velocity and distance from the plane increase progressively as shown in Fig. 1. Thus, if dust is elevated above the plane to $z < 200$ pc by some mechanism (more efficient at this height), further ejection into the halo could be provided successfully by radiation pressure (Ferrara 1998) unless a magnetic field strongly suppresses dust motion in vertical direction.

Given a galaxy with a plane parallel magnetic field, it may well be that under the combined forces of radiation and cosmic ray pressure a Parker instability is initiated as mentioned by Ferrara (1998), which forms large scale loops with a characteristic size in horizontal and vertical direction up to 1–2 kpc.

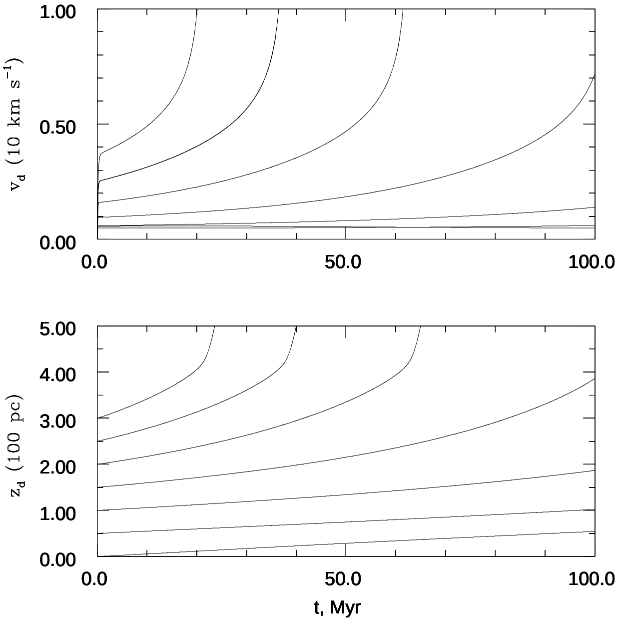

Figure 1: Velocity (upper panel) and height (lower panel) for a dust grain of $a = 0.1\ \mu$m moving through interstellar gas in vertical direction under radiation pressure: initial height above the plane $z_{init} = 0$, 50, 100, 150, 200, 250, 300 pc from the lowermost to the uppermost.

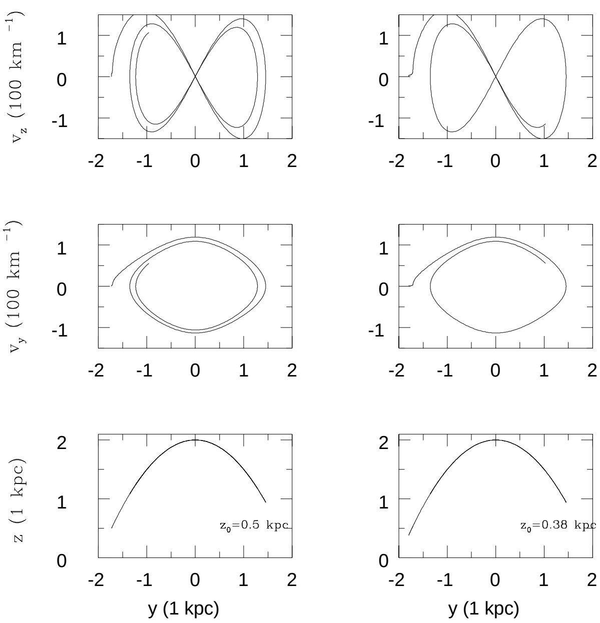

Figure 2: Trajectory (lower panel) and velocity (horizontal and vertical components as shown in upper panels) vs horizontal direction of the arch for a grain of radius $a = 0.1\ \mu$m starting from $z_{init} = 0.5$ kpc (left) and 0.38 kpc (right); the integration time in both cases is 20 Myr.

We will assume that such an arch is formed and consider now the dynamics of dust particles along it, assuming the plasma component to be in hydrodynamic equilibrium (in other words we assume that momentum transfer from dust to gas due to collisions is inefficient, which means that we concern ourselves only with distances from the plane above $z \simeq 200$ pc). Moreover, we will adopt the Dickey–Lockmann best fit for the density distribution of the gas in vertical direction. Fig. 2 shows the dependence of the velocity $\mathbf{v}_d = (vy, vz)$ of a single dust particle along the arch (as shown in the lower panel); the arch is taken in a form of parabola $z_A = 2 - 0.5y^2$ (z and y in kpc). The motion corresponds to a damped oscillation around the polar equilibrium point. It is readily seen from comparison of the left and right panels that velocity loci show a rather weak dependence on the initial position of dust grain $(y, z)_{init}$ on the arch. The initial position affects mainly the dynamic time scale: the lower a grain is located at $t = 0$, the longer is the dynamic time scale – in the examples plotted in Fig. 2 the total integration time is 200 Myr, and the particles starting from lower z_{init} (the right panel) experiences less oscillations.

3 Coherency of grain motion and dust overdensity

It is interesting that trajectories of dust grains that were located at initial time far enough above the plane ($z < 0.5$ kpc) are very close to coherent, in the sense that not only they do have almost identical velocity loci along the arch, but also are their dynamical time scales very close. It is shown in Fig. 3 where horizontal (lower panel) and vertical (upper panel) positions of grains versus time are plotted that definitely trajectories of different particles are seen to converge as they move, so that any initial density distribution of dust is concentrated along the trajectory and dust density increases. As long as at $z \sim 0.5$ kpc dust and plasma components are weakly coupled (see, Fig. 1), this means that not only dust density increases as grains move up along the arch, but also the dust to gas ratio grows. It is clear that the maximal density is reached in this case in turning points where the grain velocity vanishes. Fig. 4 shows the distribution of the dust overdensity factor which is calculated as $\delta(\mathbf{r}) = \Delta V_0/\Delta V(\mathbf{r})$, where ΔV_0 is the volume of a dust fluid element in the initial position and $\Delta V(\mathbf{r})$ the volume of same element as it reaches the position **r**.

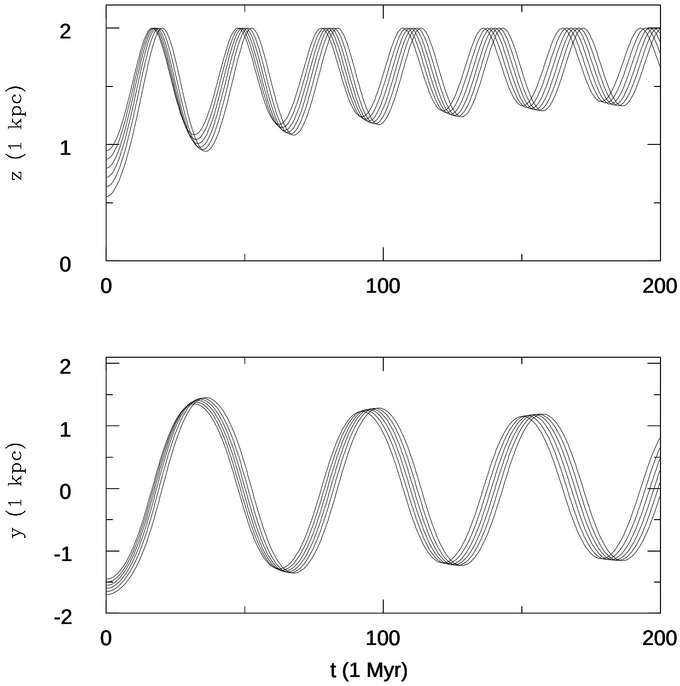

Figure 3: Position of dust particles vs time for a set of different initial heights of particles z_{init} = 0.55, 0.64, 0.72, 0.8, 0.875, 0.95 kpc from top to bottom, respectively.

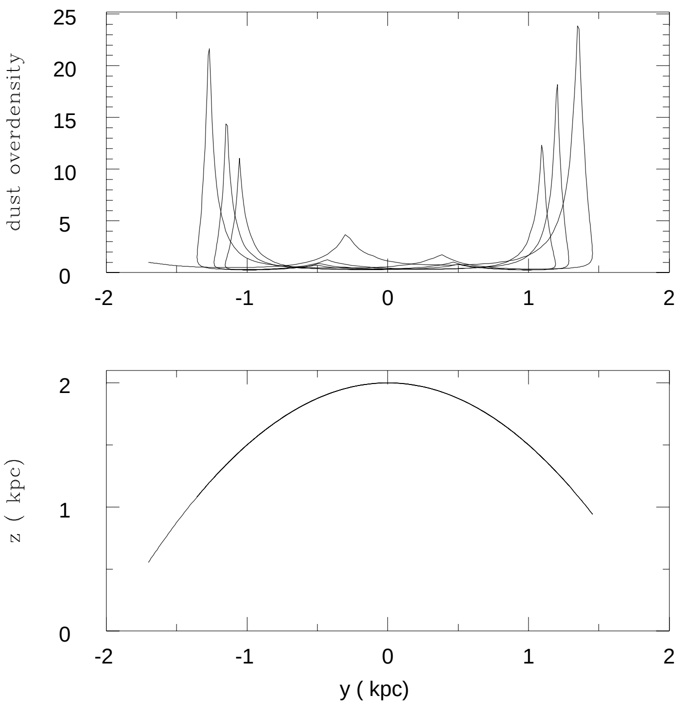

Figure 4: Density variation of a small dust fluid element contained of independent dust particles as it oscillates in the arch. The resulting dust overdensity factor can be found as the average of overlapping profiles

Now the net overdensity profile composed of many fluid elements can be imagined as the average of the one shown in Fig. 4. Motion of dust grains positioned initially at $z < 0.5$ kpc is far from being coherent – their trajectories ($y(t)$ and $z(t)$) can be shown to be divergent in the sense that their extrema are shifted considerably with respect to each other. Thus initial dust fluid elements which start their motion from $z_{init} = 0.2 - 0.5$ kpc where dust–gas collisional coupling is weak but particles do not have coherent dynamics will provide a homogeneous density distribution in the arch (with rather smooth concentration at the polar region where asymptotically all particles stop) as they fill it, and the net distribution is a superposition of the homogeneous distribution formed by particles from $z_{init} = 0.2{-}0.5$ kpc and the clumpy distribution formed by dust from $z_{init} = 0.5 - 1$ kpc.

4 Conclusions and outlook

By applying the test particle method on interstellar dust grains within a realistic halo model including a nonlinear drag force we calculated typical grain motions along a magnetic arch induced by the stellar radiation field. It could be shown that the motion of a single dust particle exhibits a damped oszillatory behaviour which finally leads to a dust overdensity not only at the foot points, but at the top of the arch as well. This clearly demonstrates that height depending drag forces lead to species separation and can efficiently contribute to the often observed structuring of the dusty interstellar medium. The dynamical time scales on which the clumping occurs in our calculations are well within a reasonable range to explain the observed structures.
At the moment more extended three-fluid calculations with the DENISIS code (Schröer et al. 1998) are carried out to further investigate the large scale three-dimensional dynamics of the dusty interstellar medium. These self-consistent simulations focus especially on the nonlinear interaction between the fluid dynamics and the evolution of the magnetic field in the galactic halo.

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