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Dusty plasmas on galactic scales

Yuri A. Shchekinov

Department of Physics, University of Rostov,
Rostov on Don, 344090 Russia

Abstract

Interstellar dust is spread in galaxies over large scales, often far beyond the stellar disks. Several mechanisms can be responsible for carrying the dust both in the vertical and radial directions, producing in general different spatial dust distributions. In spite of the small mass fraction dust can be in some cases dynamically active, and its role in star formation process and dynamics of shock waves is still not completely understood. In this review I discuss briefly the issues connected with the large scale distribution of the interstellar dust, the impact of the dust on star formation and on dynamics of shock waves.

1 Introduction

Interstellar dust grains are normally charged with the charge varying in a wide range from negative to positive, and reaches in diffuse interstellar environment hundreds of charge units (Weingartner & Draine 2001a, Yan et al. 2004). The characteristic charging time of grains is short, normally of $10^3 - 10^5$ s, what means that significant fluctuations of charge from the mean value are rare, except conditions in molecular clouds, where the mean dust charge is $-1 < \langle z_d \rangle < 0$ and part of time grains spent as neutral. Therefore, in a wide range of interstellar parameters dust particles are highly charged and involved into overall electrodynamics of the interstellar medium (ISM). Charge separation is important, though, only on short scales of relevant Debye lengths, the longest being the dust Debye length $\lambda_d = \sqrt{k_B T_d / 4\pi n_d z_d e^2} = 6 \times 10^7 T_{e,4}^{1/2} z_{d,2}^{-1/2} n^{-1/2}$ cm; $T_d = T_e$ is assumed[1]. Thus, in most cases quaineutrality condition $n_e = z_i n_i + z_d n_d$ is essential when the large scale dynamics of a dusty ISM is concerned. The dust gyrofrequency $\omega_{dc} = 10^{-10} z_{d,2} m_{d,10}^{-1} B_{\mu \mathrm{G}}$ Hz, where $m_{d,10} = 10^{10} m_{\mathrm{H}}$, and thus dust particles are tightly coupled to magnetic lines. Note, that $z_{d,2}/m_{d,10}$ varies from $\sim 10^{-2}$ for the larger grains ($a \simeq 1\mu$m) to $\sim 10^4$ for the smallest ones ($a \simeq 10$Å), with the corresponding variations of the gyrofrequency $(10^{-12} - 10^{-6}) B_{\mu \mathrm{G}}$ Hz. The contribution of the charged dust into current in the ISM is negligible $j_d/j_e \sim 10^{-10}|z_{d,2}|$, however when dust is streaming along magnetic lines it makes electromagnetic waves in the long wavelenght limit ($\lambda > 1$ pc) unstable on relatively short times, and thus can be a source of MHD turbulence in the ISM (Shchekinov & Kopp, 2004).

On microscopic scales charged dust grains can control chemical structure of forming protostellar cores through ambipolar diffusion of dust and associated evacuation of depleted elements outwards (Ciolek & Mouschovias, 1996); it can suppress magnetorotational instability in accretion protostellar disks and establish a layered accretion with a reduced accretion mass rate of refractory elements onto the central star (Gammie, 1996). On larger scales charged dust is found to be involved into turbulent MHD motions, in which they can be accelereted up

[1] $A_m = A/10^m$ in cgs

to $v \sim 10$ km s^{-1}, so that grain-grain collisions can efficiently re-eject refractory elements into the ISM (Yan et al., 2004). When we turn to the galactic scales the following aspects of the dynamics of charged dust particles are of principal significance for the interstellar matter: *i)* transport of dust particles and associated transport of heavy elements frozen on their surface; *ii)* sedimentation of dust in external gravitation and radiation fields and possible effects on star formation; *iii)* processing of dust by interstellar shock waves, destruction of dust grains and overall circulation of dust in the ISM.

2 Transport of dust

2.1 Transport in z

It was recognized during the last decade that dust is spread in galaxies both in vertical and radial directions over much larger scales than it was thought earlier. In NGC 891 dust is found quite far away from the galactic plane: $z > 0.4$ kpc and in some cases it extends up to ~ 2 kpc (Howk & Savage 1996, 1999, Rossa et al. 2004), with the total mass of gas in the extraplanar dusty structures of $\sim 2\times 10^8 M_\odot$ assuming local dust-to-gas ratio. Individual dusty structures are as massive as $\gtrsim 10^5 - 10^6 M_\odot$, and the associated potential energy $\gtrsim 10^{52} - 10^{53}$ erg. Similar dust distribution was recently reported by Thompson et al. (2004) for NGC 4212.

2.1.1 SNe

Multiple SNe explosions are commonly thought to be the principal energy source for the ejection of gas and dust into galactic haloes through chimney outflows (Norman & Ikeuchi, 1989). The required energy for a chimney to work is more than 10^2 SNe in normal conditions, i.e. in the Milky Way ISM at solar radius (e.g., Mac Low et al., 1989, Hensler et al. 1996), although it is sensitive to the gas scale height h and its velocity dispersion c_s: $E \propto c_s^2 h^3$, and can vary substantially. The fraction of OB associations which can produce such powerful events is small – for a power law luminosity function of OB associations as in the Milky Way it is only 0.04 (Shchekinov, 1996, Dettmar et al., 2005). Moreover, the mass of gas ejected into the halo by a single blowout is normally $M_e \sim (5-10)\rho_0 h^3 \lesssim 3\times 10^3 M_\odot$, where ρ_0 is the midplane density (Mac Low et al., 1989). This is obviously much smaller than the mass of dusty clumps observed in NGC 891 and NGC 4212, and therefore these clumps can be produced by the SNe activity only partly, while the rest is apparently connected with other transport mechanisms. One should stress in this respect that dust-to-gas ratio in extraplanar dusty clouds in NGC 891 can be significantly enhanced, as Dettmar et al. (2005) argue from the non-detection of Hα rims around them. If this is the case, these structures must be formed by the selective action of the radiation pressure on dust.

2.1.2 Radiation pressure

Interstellar radiation field above galactic planes is obviously anisotropic, and should act on dust particles expelling them in vertical direction (Barsella et al., 1989, Ferrara et al. 1990, 1991, Shustov & Vibe, 1995). It works however only under certain conditions. First, as interstellar dust is mostly charged it can move vertically only if the interstellar magnetic field has a significant component perpendicular to the plane. In principle, the Parker instability can produce large scale magnetic loops extending vertically up to several kpc (Kahn & Brett, 1993, Kamaya et al., 1996, Hanasz & Lesch, 2000, Steinacker & Shchekinov, 2001), in which case such magnetic loops can serve as conduits for the radiation-driven dust. Note, that radiation pressure itself is apparently not capable to trigger the large scale Parker instability. This is connected with the fact that the typical value of the volumetric radiation force $f_{\rm r} \sim \sigma\Phi n_d/c \sim 3\times10^{-35}$ erg cm^{-4} for $\Phi \sim 0.01$ erg cm^{-2} s^{-1} is much smaller than the gas or cosmic ray pressure force $|\nabla p| \sim 10^{-33}$ for $|\nabla|^{-1} \sim 100$ pc (Dettmar et al. 2005).

Second condition is connected with a drag force. The radiation force per dust grain is $F_{\rm r} \sim 3\times10^{-23}$ dyne with the corresponding acceleration of $a_{\rm g} \sim 3\times10^{-9}$ cm s^{-2} comparable to that produced by gravitation. In the midplane where the gas density is high, $n \gtrsim 0.1$ cm^{-3}, the collisional coupling of the dust and gas is fairly strong, and the radiation pressure can produce only a slow drift of the dust with respect to the gas along $\mathbf{B}$ – the drift velocity is $v_{\rm d} \lesssim 0.3-0.5$ km s^{-1} (Weingartner & Draine, 2001b). Such a slow motion requires ~Gyr time scales for the dust to be elevated up to 0.3-1 kpc above the galactic plane. However, once dust is carried out by a hydrodynamic flow (e.g. convection, or relatively weak SNe explosions) to distances $z \gtrsim 0.3$ kpc, collisions become less frequent and dust particles can be accelerated by radiation efficiently. Depending on the anisotropic radiation flux they reach the distance $z \sim 1-3$ kpc in one to several hundreds Myr, and as their motion along the loop is converging they form dense clumps in the top parts of the magnetic loops with overabundant dust (Dettmar et al., 2005). The characteristic time scale for the radiative dust transport varies as $t_{\rm R} \propto \Phi^{-1/2}$, and for NGC 891, where the radiation flux can be as high as ~ 0.1 erg cm^{-2} s^{-1}, it is $t_{\rm R} \sim 100$ Myr, while for the conditions in the Milky Way it is 400 Myr and may be too long compared to the lifetime of Parker magnetic loops.

2.1.3 Vortices and convection

Differential rotation of galactic disks stores kinetic energy of $\sim 10^{57}$ erg, which can produce the total mechanical luminosity of $\sim 3\times10^{42}$ erg s^{-1} when being released through hydrodynamical instabilities of sheared flows in spiral density waves with the growth rate $\gamma \sim |du/dr| \sim 3\times10^{-15}$ s^{-1}. This is factor of 3 higher than the energy injected by SNe $\sim 10^{42}$ erg s^{-1}. It is known that instabilities of sheared flows in external gravitational field field can result in formation of vortical motions (known as tornado cyclones) involving a powerful mass transfer in the perpendicular direction (e.g. Snow, 1982). In a simplified self-similar solution for a galactic tornado flow Shchekinov (2004) estimated the mass ejection rate by a single tornado as $\dot{M}_{\rm ss} \sim 0.001-0.01\ M_\odot$ yr^{-1}, and the total mass ejected into the halo in one lifetime $M_{\rm ej} \sim 10^4-10^5 M_\odot$, which is comparable to the mass of an individual dusty clump inferred by Howk & Savage (1999) and Thompson et al. (2004) for NGC 891 and NGC 4212 haloes.

Convective motion associated with spiral density waves is a supplementary source for elevation of dust along with gas into the halo. In numerical simulation of a 3D hydrodynamics of spiral density waves Gómez & Cox (2002) found efficient bore flows extending up to $z \sim 1.5-2$ kpc with characteristic velocities $\sim 50-60$ km s^{-1}, thus providing the mass circulation rate of up to 1-3 $M_\odot$ yr^{-1} for the parameters of the Milky Way ISM.

2.2 Transport in R

Observations of spiral galaxies in FIR show that dust extends in the radial direction far beyond the stellar or CO disks. Neininger et al. (1996) reported for NGC 4565 that the dust 1.2mm continuum emission has a radial scale length twice as the scale length of the CO emission. Bianchi et al. (2000) found for 7 spiral galaxies observed by ISO that they have the 200μm emission distributed in the radial direction much wider than the blue light. The corresponding dust-to-star radial scale length they inferred is $R_d/R_* > 1.5$. Moreover, in the case of NGC 6946 the best fit model of the FIR spectrum shows $R_d/R_* \gtrsim 3$. In absolute values the difference between R_d and R_* can be as large as $3-10$ kpc, and thus a powerful mechanism for radial transport of dust is wanted.

2.2.1 Turbulence and radiation pressure

It is readily seen that turbulence is not sufficiently fast to provide migration of dust in the radial direction: with the turbulent diffusivity $D_{\rm t} \simeq Lv/3 \sim 10^{26}$ cm^2 s^{-1} what corresponds to the characteristic length $L \sim 100$ pc, and the velocity dispersion $v \sim 10$ km s^{-1}. The rms displacement $\sqrt{\langle \Delta r^2 \rangle} \sim 3$ kpc can be reached in $\sim 5 \times 10^{17}$ s.

In outer regions of the galactic disks, interstellar radiation field is anisotropic. Weingartner & Draine (2001c) found the anisotropy of radiation at the solar circle ranging from 3% to 21% for optical (5500Å) and UV (1500Å) starlight. This forces dust particles to drift along magnetic lines with the velocity $v_{\rm d} \sim 0.5$ km s^{-1} (Weingartner & Draine, 2001b). In the radial direction the radiation forced drift is suppressed by the magnetic field by a factor $\omega_B \tau_d \gtrsim 10^2$, where ω_B is the dust gyrofrequency, τ_d is the drag time for a grain. In principle, as noted by Cho et al. (2003), in a relatively weak magnetic field MHD turbulence can provide as high dust diffusivity as the hydrodynamic turbulence does. However, as mentioned above even the hydrodynamic turbulence is too slow to carry dust over the scales $\gtrsim 3$ kpc in reasonable time.

Shaginyan & Shchekinov (2004) suggested a combined scenario with the anisotropic radiation pressure accelerating dust particles in the radial direction outwards in those small scale regions of a turbulent magnetized ISM, where the random magnetic field is predominantly radial. In this scheme dust particles accumulate in the local magnetic valleys (with respect to the radial direction), where the radial component vanishes and the magnetic field becomes predominantly azimuthal. On next stage accumulated dust diffuses into a neighbour turbulent eddy through reconnection and the radiation drift continues futher. The characteristic drift velocity in this scenario depends on the radiaton drif velocity $v_{\rm d}$ and the reconnection time, and when the latter is not particularly small it is close to $v_{\rm d}$. The corresponding time for the dust to diffuse over a 3 kpc radial scale is of the order of 1 Gyr.

2.2.2 Spiral density waves

Spiral density waves disturb differential rotation of the gas and impart to it the radial velocity component, thus providing radial migration of dust particles by the drag and the spiral gravity force. Vorobyov & Shchekinov (2004) have explored this possibility for a two-fluid (gas and dust) system evolving in an external gravitational potential from the stellar disk and dark matter halo. The dust being injected at the initial time uniformly inside the corotation radius ($r \leq 6.5$ kpc), forms a spiralwise distribution in one rotation period of the galaxy with the arms extending outside the corotaion (Fig. 1). In approximately 1.5 rotation period dust arms reach radial distances almost twice the corotation radius ($r \simeq 10$ kpc), with 5-10% of the initial dust mass found in this region. Quite important is that the dust arms are clearly offset of the gas ones, revealing variations of the dust-to-gas ratio by factor more than 10-30 between the dust and gas arms. Moreover, a significant fraction (~30%) of the injected dust migrates most of its time ~ 1 Gyr in the region between the gas arms, and thus can survive against a hostile influence of strong shocks from SNe inside the gas arms.

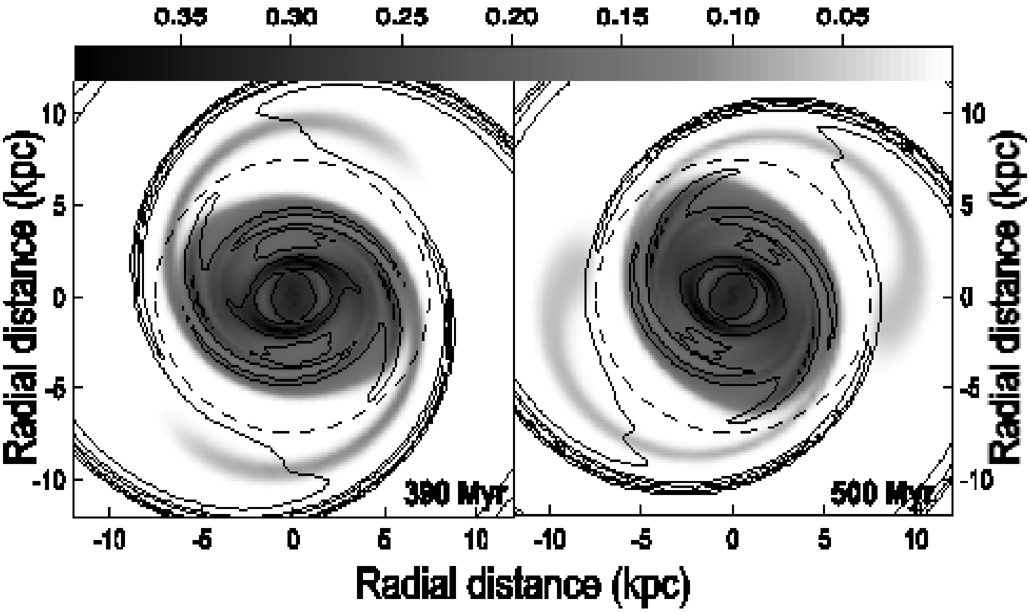

Figure 1: Contour plot of the gas spiral wave superimposed on the gray scale map of the dust spiral wave for 390 and 500 Myr since when the dust was injected uniformly inside the corotation radius $r < 6.5$ kpc; the dashed circle outlines the corotation in the gas disk (from Vorobyov & Shchekinov, 2004). The scale bar is in $M_{\odot}$ pc^{-2}.

3 Star formation

Dust is known to be an important agent in star formation through its contribution to thermodynamics and optical characteristics of the gas and its ability to affect the abundances of the depleted elements in star-forming regions. At present, it becomes clear that dust can be also dynamically important in star formation. Theis & Orlova (2004) have found that a small addition of a cold dust component (2% by mass) can strongly destabilize even hot galactic gaseous disks with a high Toomre parameter $Q = 2 - 3$. The growth rate of the instability depends on the dust-to-gas ratio, so that nonlinear dust structures develop in ~ 13 galactic rotation periods for dust admixture of 2% by mass, and in ~ 6 rotation periods for 10% of dust mass fraction. The instability results in formation of overdense gas and dust structures with a charactersitic size in the radial direction of 100-200 pc, which can, in principle, give rise to molecular clouds. At present, however, a growing number of theoretical arguments appeared favouring the interstellar dust to be quite a hot component. Yan et al. (2004) advocate that MHD waves heat dust particles to the velocity dispersion of 10 km s^{-1}. This means that in relatively cold HI clouds with $T \lesssim 100$ K, the contribution of such “hot” dust particles to pressure can be comparable with the gas pressure. In these conditions dust can stabilize gravitational instability and suppress star formation.

An example of physical conditions when dust can be dynamically active in triggering star formation was suggested by Cammerer & Shchekinov (1994). In optically thick clouds interstellar UV produces extraheating and an increase of pressure in the external layers by photoelectrons from dust grains. This leads to squeezing of the cloud and stimulate subsequent gravitational compression. This effect was possibly observed by Hester et al. (1996).

Radiation pressure is known to trigger in a medium with a homogeneous dust distribution the so-called "mock gravity" instability (Field, 1971). The necessary condition for the instability to grow is that the ratio of the radiation to gas energy density $\rho_{\rm r}/\rho_{\rm g}$ was sufficiently large. In the long-wavelength limit, $\lambda > L_{\rm d}$ ($L_{\rm d}$ being the extinction length), the required condition is $\rho_{\rm r}/\rho_{\rm g} > 1$, and thus is close to be fulfilled in the regions with the gas pressure $P \lesssim 3 \times 10^3$ K cm^{-3}. The characteristic masses for this instability $M_{\bar{\rm g}} \sim 10^6 \zeta_d^{-3} n^{-2} M_\odot$, where $\zeta_{\rm d}$ is the dust-to-gas ratio in units of the mean Milky Way value, can be reasonable for typical ISM conditions. The growth time, though, is normally longer than the gravitational free-fall time $t_{\rm ff}$: $t_{\bar{\rm g}} \sim 10^8 \zeta^{-1} n^{-1}$ yr. In those regions, however, where dust is overabundant due to the action of selective forces (such as radiation pressure) $t_{\bar{\rm g}}$ can decrease considerably and become even shorter than $t_{\rm ff}$. From this point of view the "mock gravity" seems capable to act in the extraplanar dusty clouds, such as observed in NGC 891 and NGC 4212, if they have an enhanced dust-to-gas ratio as advocated by Dettmar et al. (2005). Note in this connection detection of several extraplanar regions of recent star formation in the edge-on galaxy NGC 55 by Tüllmann et al. (2003). Observations of possible pecularities in abundances of refractory elements in these HII regions would indicate whether the radiation pressure contributed to initiation of star formation through the selective action on dust particles.

4 Dust in magnetized shocks

Interstellar shock waves are the principal source of dust destruction (see review by Draine 2003). In most cases interstellar dust behind shock waves is treated as a passive component having minor effects on dynamics of the shocked gas. However, dust grains can be dynamically active in oblique shocks and can affect their structure and evolution through the instability similar to the mirror instability in plasma. In radiative shocks gas density increases $\rho \propto T^{-1}$ and results in an encrease of the frozen-in magnetic field $B_{||} \propto \rho$. Due to the betatron acceleration the transverse velocity dispersion of dust grows as $v_{d,\perp}^2 \propto B_{||}$, so that the dust component behind the shock can become highly anisotropic with the transverse dust pressure comparable to the gas one (McKee et al., 1987). In these conditions oblique perturbations with $k_\perp \neq 0$ are unstable with the growth rate $\omega \sim \sqrt{\beta_{d,\perp}} k_{||} v_{d,\perp}$, $\beta_{d,\perp}$ being the partial transverse dust pressure (Shaginyan & Shchekinov, 2004).

Another aspect connected with interaction of the shock waves and the interstellar dust relates to segregation of dust and variations of the dust-to-gas ratio in the ISM. Oblique shock waves can produce spatial separation of the dust and gas. When passing through the shock front with a gradiant of magnetic field parallel to the front, $dB_{||}/dz \neq 0$, dust particles decellerate and experience mirroring when move along the front. At the stagnation point, where their longitudinal kinetic energy vanishes, they accumulate and form dusty troughs with an enhanced dust-to-gas ratio (Shaginyan & Shchekinov, 2004).

5 Conclusions

A common feature of many mechanisms carrying dust in the ISM is that they act selectively, and result in segregation of dust:

- Interstellar radiation field can be an efficient agent for the dust transport both in the vertical and radial directions, and as it acts on the dust particles selectively it produces regions with overabundant dust. The origin of the dusty structures in the haloes of NGC 891 and NGC 4212 can be connected with the radiation pressure.

- Spiral density waves can drive dust in the radial direction outward. In this case a combined action of the gravitational field of the spiral wave and the collisional drag force result in spatial separation of the dust and gas, and provide large scale variations of the dust-to-gas ratio.
- Passing through oblique magnetized shocks dust particles can be segregated on the scales of nonuniformity of the magnetic field behind the shock front.

Interstellar dust can be a dynamically active component in structuring the ISM:

- Interstellar dust can be dynamically important in regulation of star formation process. Depending on the kinetic temperature of the dust it can either stimulate gravitational instability when it is cold, or can be a suppressing factor if it is kinetically hot.
- Dust particles heated by the betatron mechanism can destabilize interstellar oblique shock waves.

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