Modeling of dust evolution in the Milky Way

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ABSTRACT

The results of modeling dust evolution in the ISM of the Galaxy are presented. We combine a chemical evolution model of the Galaxy with a model for dust evolution in the ISM. Dust growth in the ISM and destruction by supernova shocks are included. To study dust growth in molecular clouds we develop a new model, in which dust production is determined by characteristic growth timescales of dust species in molecular clouds. We study carbon, silicates, iron and SiC dust species, discriminating between dust injected by AGB stars and supernovae, and dust grown in the ISM. The observed abundance ratios of presolar dust grains formed in SN ejecta and in AGB outflows require that for the ejecta from supernovae the fraction of refractory elements condensed into dust is quite small (10^{-2} to 10^{-4})

Subject headings: galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction — ISM: structure

1. Introduction

The composition and origin of dust population in the ISM is a long term issue for discussions. It is known from observations and presolar grain studies that dust grains condense in stellar winds of AGB stars and SNe. While AGB stars are well known dust factories, the situation with dust production in supernovae is less clear. There are only a few abundance determinations of dust from SN spectra available, which results mainly in low dust condensation degrees in SNe (Ercolano et al. (2007)). This low efficiency of SN dust production questions the origin of dust in young high redshifted objects. Besides star-dust condensed in stellar sources, there is a strong evidence of dust growth and coagulation in molecular

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clouds (MCs) (e.g. Savage & Sembach (1996)). Dust grown in the ISM under low temperature conditions should have properties quit different from star-dust and lose any isotopic anomalies typical for star-dust.

Both star-dust and ISM-grown dust cycle between ISM phases undergoing destruction in the warm medium on short timescales of $0.4 - 0.6$ Gyr (Jones et al. (1996)). Therefore, a detailed model of dust evolution in the ISM should account for dust injection from stars, dust production by MCs, and processing of dust in the ISM. So far a simple one-zone model of the evolution of dust and gas content of the galaxy has been developed that successfully reproduces averaged dust properties in the disk in Dwek (1998), but no attempt has been made to model the evolution of dust species from different sources. To understand the origin of dust and the contribution of different sources of dust production during galactic evolution, we construct a model that discriminates between dust from AGB stars, SNe and ISM-grown dust (Zhukovska et al. 2008). In recent time a huge progress has been achieved in studies of presolar dust grains in meteorites that provide insight into the relative role of SN and AGB dust at the instant of the Solar System formation. In combination with recently calculated metallicity-dependent dust yields from AGB stars (Ferrarotti & Gail (2006)) it allows us to make independent estimates of the degree of dust condensation in supernovae. Since the evolution of dust is closely related to the multi-phase structure of the ISM, our model accounts for it in an approximate way using fraction of molecular clouds and their lifetimes from observations of the Milky Way.

2. Model

We combine a standard model for chemical evolution of the Galactic disk with a detailed model for dust in a way similar to that of Dwek (1998). We assume a two-infall model of galaxy formation in which the Milky Way is formed in two episodes on different timescales. For massive galaxies as the Milky Way one can neglect the outflows, so the total density of the disk is entirely determined by the infall. We normalize the infall rates to reproduce the present radial density profile in the galactic disk, which is approximated by two exponential disks corresponding to the thin and thick disks.

In this model the chemical evolution of the ISM is determined by the heavy element input from SN II, SN Ia and AGB stars and the infall of gas. Our prescriptions for the stellar nucleosynthesis are given in details in Zhukovska, Gail & Trieloff (2008), and will not be repeated here. We notice that new SN II yields from Nomoto et al. (2006) allow to reproduce much better the abundance ratios between main dust-forming elements than the widely used Woosley & Weaver (1995) yields, which it is crucial for the dust mixture.

The model reproduces sufficiently well a standard set of observational constraints for the chemical evolution models as well as observations of dust in the Solar vicinity (Zhukovska, Gail & Trieloff (2008)). We also test the model for the radial profiles of main observed quantities. Comparison of the metallicity gradient from model calculations for instants from 1 to 13 Gyr with observations is presented in the left panel of Fig. 3.

For the first time our dust model treats dust from AGB stars, SNe type II and Ia, and dust produced in MCs as separate components. Although a big number of different dust species is known to be produced in stars, we include only the evolution of four main dust species: carbon, silicate, SiC and iron dust. Our model is based on three essential elements:

- *Dust from AGB stars.*

  We implement the metallicity dependent dust yields for dust production by AGB stars, which result from the first consistent calculations of dust condensation in stellar winds with M-, S- and C-star chemistry combined with stellar evolution calculations on the AGB from Ferrarotti & Gail (2006)).

- *Dust from supernovae.*

  Dust condensation in SNe is described by a simple parametrization as in Dwek (1998). We estimate the condensation efficiencies of dust production by supernovae by fitting the SN II to AGB dust ratio, predicted by the model at instant of the Solar System formation, to that measured from presolar dust grains in meteorites. Laboratory investigations of presolar grains are available for silicate, SiC, and with somewhat less certainty for carbon grains. The estimates obtained in this way are then used in the final model calculations of dust evolution.

- *Dust production in molecular clouds.*

  We develop a new approach for dust growth in MCs due to accretion of key elements from the gas phase. The production rate by MCs is determined by the lifetime of the clouds, for which we take an averaged observed value of 10 Myr, and characteristic growth timescales of dust species given by

  $$\tau_{\rm gr} = 0.54\,\nu_{\rm c}\,A_{\rm m}^{\frac{1}{2}}\,\rho_{\rm c}\,A_{\rm c}^{-1}\,(\epsilon\,N_{\rm H})^{-1}\ {\rm Myr},$$

  The quantities $\nu_{\rm c}$ and $A_{\rm c}$ are the number of atoms of key element in the formula unit of the condensed phase and its atomic mass, respectively, $A_{\rm m}$ atomic mass of growth species, $\rho_{\rm c}$ the bulk mass density of dust. They are constants determined by properties of dust species. The element abundance ϵ of the key element, resulting from the chemical evolution of the ISM, varies significantly during evolution. Growth timescales for densities typical for molecular clouds for main dust species are presented in Fig. 1. Note that growth timescale is inversely proportional to the hydrogen density N_H, so that in the warm medium it is 3-5 orders of magnitude larger than in MCs and much longer than the cycling timescale between clouds and intercloud medium that is equivalent to the lifetime of the cloud. Therefore, only growth in molecular clouds is fast enough for efficient dust production.

The fraction of molecular clouds in the galactic disk is fixed during calculations to an observed value in the Milky Way disk. Modeling of the Milky Way's dynamical evolution with 3-d multi-phase ISM in Harfst et al. (2006) justifies this approximation to some extent. They show that the galaxy reaches quasi-equilibrium between ISM phases soon after the onset of simulations.

3. Results

Figure 2 shows model results for the evolution of dust abundances of the various dust species for the Solar vicinity for the 13 Gyr of evolution of the galactic disk. The dust components with index "ISM" are isotopically normal grains grown in the interstellar medium. MC-grown dust dominates dust mass during most of the evolution except for the very earliest time and low metallicities, when only supernovae contribute to dust content.

According to our estimates of efficiencies of dust production in supernovae, SN dust is only a minor fraction of interstellar dust. By requiring the mass fraction of carbon, SiC and silicate grains with SN origin to reproduce the value observed in meteorites, we reveal that supernovae mostly produce carbon dust. Derived in this way efficiency of carbon dust production in SNe of $0.04 - 0.30$ is much higher than our estimates for silicate and SiC dust of only 3.5×10^{-4} and 5×10^{-4}, respectively. These results can be explained by the fact that mixing between different layers in SN expanding shell is required to form silicate and SiC grains, since carbon and silicon are synthesized in different layers, while formation of graphite requires only carbon atoms and no mixing. Thus the population of stardust in our model is mostly dominated by AGB stardust because of low dust production efficiency in SNe, except the first 2 Gyr delay due to the longer lifetimes of low and intermediate mass stars.

Figure 3 depicts the radial dependence of dust abundances in the Milky Way at present time. Change in dust composition along radius is due to a metallicity gradient in the galaxy, which is depicted for illustration at the right panel of Fig. 3. A weak dependence of SN dust production on galactic radius reflects that most of the heavy elements are produced directly in SNe and dust production, thus, does not strongly depend on initial metallicity of the star. However, this is not the case for dust from AGB stars, which reveal the strongest dependence of ejected dust composition on Z_*. At low metallicities AGB stars produce mainly carbon dust.

The model calculations predict strong variations of dust composition along galactocentric radius with time. For instance, the change in mass fraction of carbon dust is shown in Fig.4 for instants from 1 to 13 Gyr. At the early stage of galaxy evolution the dust content is mostly determined by injection of carbon dust from SNe, which provide seeds for subsequent growth of carbon dust in MC. The situation changes dramatically as soon as the metallicity of the ISM exceeds 10^{-3} and efficient silicate production commences in MCs. Later on the carbon to silicate dust ratio remains approximately constant.

4. Conclusions

Accordingly to our model calculations the dust content of the galaxy is mostly determined by dust condensation in molecular clouds, which starts, when the metallicity of the ISM exceeds a critical value of about 10^{-3}. SNe can not be the main sources of dust in the early Universe, but supply initial seed grains for dust growth in the ISM. We would like to point on the difference in dust composition at low metallicities, for which our model predicts mainly carbon dust. The present model of dust and gas evolution is shown to reproduce well observational constraints for the Milky Way. The general approach can be also applied for modeling other disk galaxies and dwarf galaxies once the density distribution, star formation rate and metallicity at present time are fixed from observations. Also, the dust production by molecular clouds depends on their mass fraction and lifetime, therefore observations of the cold phase of the ISM are needed for realistic modeling dust evolution in the ISM.

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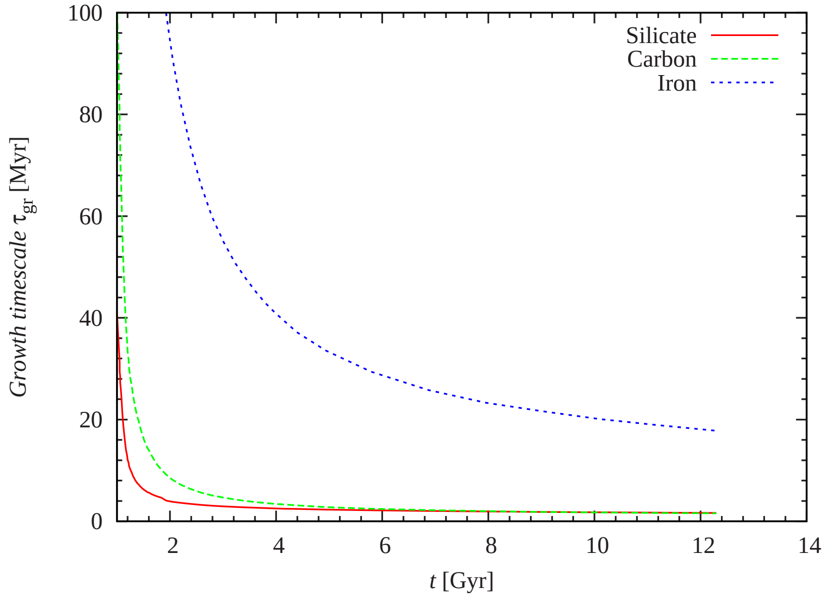

Fig. 1.— Growth timescale for the silicate, carbon, iron dust species growing in molecular clouds for the Milky Way model at the solar circle.

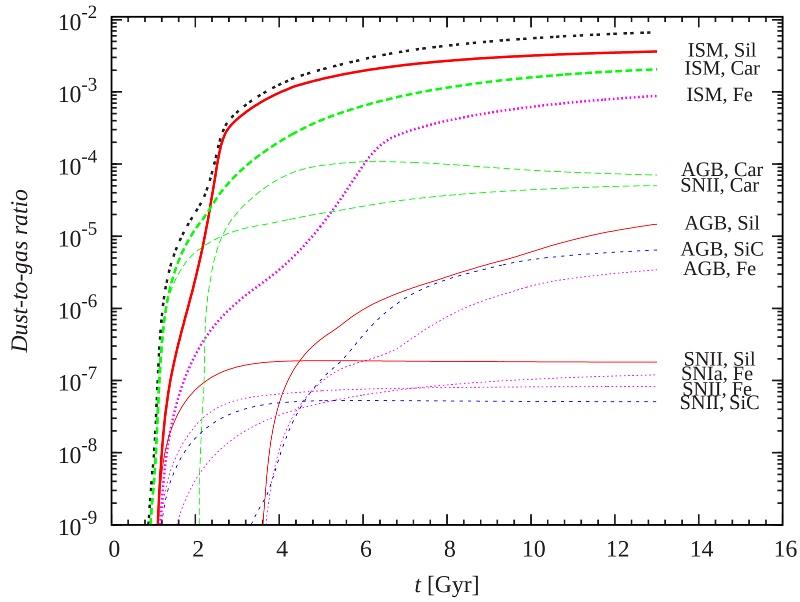

Fig. 2.— Time evolution of dust abundances at Solar circle as predicted by the model. Dust condensed in molecular clouds denoted as ISM dust dominates dust mass during most of Galaxy evolution. Black thick line shows the evolution of total dust-to-gas ratio.

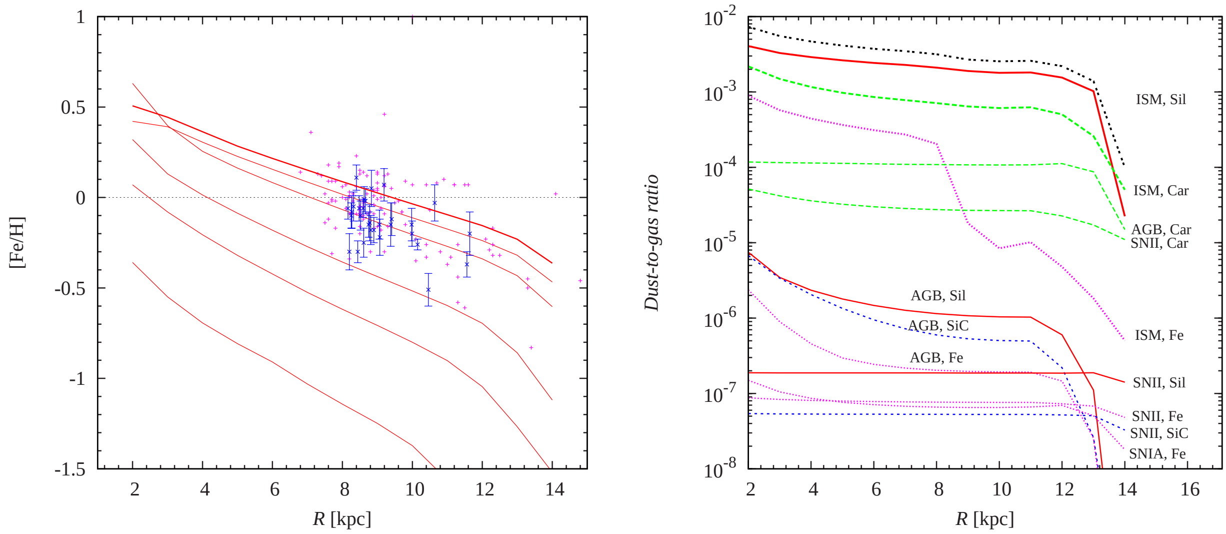

Fig. 3.— *Left Panel.* Metallicity gradient in the Milky Way disk as predicted by the model calculations at instants 1-13 Gyr (solid line from bottom to top) and observations (dots and errorbars). *Right Panel.* Radial dependence of dust abundances in the Milky Way at present time. Black thick line shows the variation of total dust-to-gas ratio.

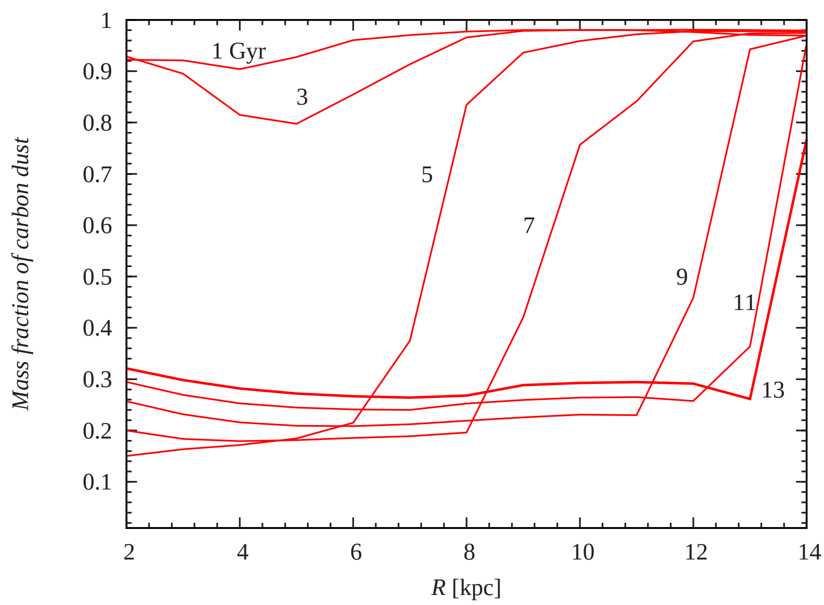

Fig. 4.— Variations of mass fraction of carbon dust with galactic radius for model calculations of Milky Way at instants from 1 to 13 Gyr. Carbon dust dominates the dust content at low metallicities at the early phase of the evolution and in the outer parts of the galaxy.

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