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Dust-to-Gas Ratio and Phase Transition of Interstellar Medium

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Abstract. We discuss the time evolution of dust-to-gas mass ratio in the context of multi-phase model of interstellar medium. Phase transition of interstellar gas is considered to occur on a timescale of $\sim 10^{7-8}$ yr, according to a nonlinear open system model of interstellar medium. Since the phase transition changes the dust formation and destruction rates, the dust-to-gas ratio also fluctuates on the same timescale. This explains the scatter of the dust-to-gas ratios of spiral galaxies quantitatively, though we should note the large observational uncertainty.

Key words: ISM: clouds – dust, extinction – galaxies: evolution – galaxies: ISM — galaxies: spiral

1. Introduction

Recent chemical evolution models of galaxies including the dust content are successful in explaining the dust amount of nearby galaxies (Wang 1991; Lisenfeld & Ferrara 1998; Dwek 1998; Hirashita 1999a, hereafter H99; see also Takagi, Arimoto, & Vansevičius 1999). Supernovae (SNe) are the dominant source of the formation of dust grains (Dwek & Scalo 1980), and SN shocks destroy grains (Jones et al. 1994; Borkowski & Dwek 1995). Thus, in those models are dust content connected with star formation histories.

In our previous work, H99, the dust-to-gas ratio was expressed as a function of metallicity (see also Lisenfeld & Ferrara 1998), which is also related to star formation histories. It confirmed the suggestion proposed by Dwek (1998) that the accretion process onto preexisting dust grains is efficient in spiral galaxies. However, since the accretion is effective in cold clouds, the global efficiency of the accretion depends on the fraction of the gas in cold phase (Seab 1987; McKee 1989; Draine 1990). Thus, the efficiency varies on a timescale of $\sim 10^{7-8}$ yr by the phase transition of the ISM (Ikeuchi 1988; McKee 1989).

In this Letter, we combine the framework of H99 with a theoretical work on multiphase ISM by Ikeuchi & Tomita

(1983), whose limit-cycle model of the ISM phase transition is applied to the result in Tomita, Tomita, & Saitō (1996) by Kamaya & Takeuchi (1997; hereafter KT97). In the limit-cycle model, mass fraction of each phase oscillates continuously because of mass exchange among the components of the phases. The timescale of the phase transition in the model is determined by a few parameters intrinsic to a spiral galaxy; sweeping rate of SN shocks, evaporation rate of the cold gas, and the cooling rate of the gas heated by SN shocks. Actually, a static solution as well as the limit-cycle solution for the filling factors of the three components is possible depending on the parameters. However, the oscillatory behaviour (i.e., the limit-cycle model) of the filling factors is supported observationally. Indeed, the observed scatter of the far-infrared-to-optical flux ratios of spiral galaxies (Tomita, Tomita, & Saitō 1996) is interpreted through the limit-cycle model in KT97. KT97 suggested that the fraction of the gas mass (i.e., the mass filling factor) in the cold phase changes in the range of 0.1 to 0.7 (or more) on the timescale of 10^{7-8} yr (see also Korchagin, Ryabtsev, & Vorobyov 1994).

This Letter is organized as follows. In §2, we investigate the variation of the dust-to-gas ratio due to the phase transition of ISM in spiral galaxies. Finally, we discuss the result in §3.

2. Grain growth in multiphase interstellar medium

The ISM in a spiral galaxy is composed of multiphase gas. McKee & Ostriker (1977) constructed the model of the ISM with three components in a pressure equilibrium: the cold phase ($T \sim 10^2$ K and $n \sim 10$ cm $^{-3}$), the warm phase ($T \sim 10^4$ K and $n \sim 10^{-1}$ cm $^{-3}$), and the hot phase ($T \sim 10^6$ K and $n \sim 10^{-3}$ cm $^{-3}$). Since the mass of the hot component is negligible in a galactic disc compared with the others, we only consider the warm and the cold gas.

Dwek (1998) and H99 showed that the accretion of heavy elements onto preexisting dust grains is the dominant process for the growth of the dust content in spiral

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galaxies. Thus, we concentrate on the effect of the phase transition on the accretion.

The timescale of the grain growth through the accretion of heavy element, τ_{grow} , can be estimated by the duration of the collisions between heavy-elements atom and grains. According to Draine (1990), $\tau_{\text{grow}} \simeq 5 \times 10^7$ yr in cold gas. Here, we should note that the accretion process is more effective in denser environments. The efficiency of the accretion is proportional to the square of the gas density if metallicity and dust-to-gas ratio are the same, since the densities of both metal and dust contribute to the efficiency. Therefore, among the three components of the ISM, we only consider the accretion process in the cold gas, the densest component of the ISM.

According to H99, the increase rate of dust mass by the accretion process in a galaxy, $[dM_d/dt]_{\text{acc}}$, is expressed as

$$\left[\frac{dM_d}{dt} \right]_{\text{acc}} = \frac{\mathcal{D}M_g(1-f)}{\tau_{\text{acc}}}, \quad (1)$$

where \mathcal{D} is the dust-to-gas mass ratio, M_g is the total mass of ISM in the galaxy (i.e., $M_d = \mathcal{D}M_g$), f is the fraction of the metal in dust phase, and τ_{acc} is the accretion timescale of heavy elements onto dust grains (see Eq. 3 in H99). We note that the newly introduced parameter τ_{acc} is different from τ_{grow} , since τ_{acc} is the accretion timescale averaged over all the ISM phases. As commented above, the dust in the cold gas dominantly contributes to the accretion process. Thus, $[dM_d/dt]_{\text{acc}}$ can also be expressed in the following way:

$$\left[\frac{dM_d}{dt} \right]_{\text{acc}} = \frac{\mathcal{D}X_{\text{cold}}M_g(1-f)}{\tau_{\text{grow}}}, \quad (2)$$

where X_{cold} represents the mass fraction of the cold phase to the total mass of ISM. Here, we assume that the values of \mathcal{D} and f are constant for each phase. McKee (1989) showed that the mixing of phases makes the difference in the \mathcal{D} values among phases negligible. We also expect that f is treated as constant for all phases because of the mixing (Tenorio-Tagle 1996). Combining equations (1) and (2), we finally obtain

$$\tau_{\text{acc}} = \frac{\tau_{\text{grow}}}{X_{\text{cold}}}. \quad (3)$$

According to Ikeuchi (1988) and KT97, X_{cold} can vary with the range of $0.1 \lesssim X_{\text{cold}} \lesssim 0.7$ in 10^{7-8} yr. Therefore, from equation (3), we see that τ_{acc} varies in the range of $1.4\tau_{\text{grow}} \lesssim \tau_{\text{acc}} \lesssim 10\tau_{\text{grow}}$ on that timescale.

3. Discussions

We have shown in the previous section that the parameter τ_{acc} , the typical timescale of accretion of heavy elements onto dust grains, changes on a timescale of 10^{7-8} yr through phase transition of ISM. The range of τ_{acc} is estimated as $1.4\tau_{\text{grow}} \lesssim \tau_{\text{acc}} \lesssim 10\tau_{\text{grow}}$, which is typically 7×10^7 yr $\lesssim \tau_{\text{acc}} \lesssim 5 \times 10^8$ yr. This means that

the parameter β_{acc} (proportional to the efficiency of the accretion of heavy elements onto preexisting dust grains), defined in H99, changes by nearly an order of magnitude. Moreover, the timescale of the variation is much shorter than the typical timescale of the gas consumption in a galactic disc ($\gtrsim 1$ Gyr; Kennicutt, Tamblyn, & Congdon 1994). Thus, the dust-to-gas ratio in a spiral galaxy experiences a short-term ($\sim 10^{7-8}$ yr) variation with the amplitude of an order of magnitude.

The short-term variation can be tested by examining nearby spiral galaxies. The dust-to-gas ratios of the spiral galaxies shows scatter around their mean values even if the metallicity is almost the same (Issa, MacLaren, & Wolfendale 1990; see also H99). According to Figure 1 in H99, the theoretical lines almost reproduce the observed values. However, the dust-to-gas ratios of the Galaxy and M31 differ by several times. Both the galaxies lie in a range of $5 \lesssim \beta_{\text{acc}} \lesssim 20$. This means that we can explain the dust-to-gas ratios of these galaxies if β_{acc} changes by more than 4 times. Indeed, the discussion in §2 demonstrated that β_{acc} can change by more than 7 times on $\sim 10^{7-8}$ yr because of the phase change of ISM. Thus, it is possible to explain the scatter of the dust-to-gas ratios of spiral galaxies by considering the phase transition.

As for dwarf galaxies, we need another way to approach them, since the heavy element accretion in dwarf galaxies is much less efficient than spiral galaxies due to their small metallicity (Hirashita 1999b). Because of their shallow gravitational potential, the mass outflow (e.g., Mac Low & Ferrara 1999) can be responsible for the dust-to-gas ratio spread, as emphasized by Lisenfeld & Ferrara (1998).

We only have considered the dust formation process. However, we should also consider dust destruction. The dominant dust destruction occurs in the warm and hot phases in which SN shock waves propagate (Seab 1987). This means that the destruction efficiency is expected to show anticorrelation with X_{cold} . If a galaxy is in a higher- X_{cold} state, the dust destruction is more inefficient whereas the dust growth is faster. Thus, the variation of dust-to-gas ratio may become larger if we take into account the dust destruction.

Finally, we should note that it is still probable that the scatter is caused by observational uncertainty, since the dust-to-gas ratio is not a direct observable. However, from the discussion in §2, we can still propose that the dust-to-gas ratio varies on a timescale of $\sim 10^{7-8}$ yr by nearly an order of magnitude.

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