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, $\tau_{\rm grow}$, can be estimated by the duration of the collisions between heavy-elements atom and grains. According to Draine (1990), $\tau_{\rm grow} \simeq 5 \times 10^7$ 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, $[dM_{\rm d}/dt]_{\rm acc}$, is expressed as

$$\left[\frac{dM_{\rm d}}{dt}\right]_{\rm acc} = \frac{\mathcal{D}M_{\rm g}(1-f)}{\tau_{\rm acc}}, \tag{1}$$

where $\mathcal{D}$ is the dust-to-gas mass ratio, $M_{\rm g}$ is the total mass of ISM in the galaxy (i.e., $M_{\rm d} = \mathcal{D}M_{\rm g}$), f is the fraction of the metal in dust phase, and $\tau_{\rm acc}$ is the accretion timescale of heavy elements onto dust grains (see Eq. 3 in H99). We note that the newly introduced parameter $\tau_{\rm acc}$ is different from $\tau_{\rm grow}$, since $\tau_{\rm acc}$ 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, $[dM_{\rm d}/dt]_{\rm acc}$ can also be expressed in the following way:

$$\left[\frac{dM_{\rm d}}{dt}\right]_{\rm acc} = \frac{\mathcal{D}X_{\rm cold}M_{\rm g}(1-f)}{\tau_{\rm grow}}, \tag{2}$$

where $X_{\rm cold}$ 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

$$\tau_{\rm acc} = \frac{\tau_{\rm grow}}{X_{\rm cold}}. \tag{3}$$

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

3. Discussions

We have shown in the previous section that the parameter $\tau_{\rm acc}$, 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 $\tau_{\rm acc}$ is estimated as $1.4\tau_{\rm grow} \lesssim \tau_{\rm accr} \lesssim 10\tau_{\rm grow}$, which is typically 7×10^7 yr $\lesssim \tau_{\rm accr} \lesssim 5 \times 10^8$ yr. This means that the parameter $\beta_{\rm acc}$ (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 $5 \lesssim \beta_{\rm acc} \lesssim 20$. This means that we can explain the dust-to-gas ratios of these galaxies if $\beta_{\rm acc}$ changes by more than 4 times. Indeed, the discussion in §2 demonstrated that $\beta_{\rm acc}$ 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 $X_{\rm cold}$. If a galaxy is in a higher-$X_{\rm cold}$ 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.

Acknowledgements. We would like to thank A. Ferrara, the referee, for careful reading and useful comments that improved this Letter. We acknowledge T. T. Takeuchi for kind helps and invaluable discussions. We are grateful to S. Mineshige for continuous encouragement. This work is supported by the Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists. We made extensive use of the NASA's Astrophysics Data System Abstract Service (ADS).