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Dust evolution with active galactic nucleus feedback in elliptical galaxies

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ABSTRACT

We have recently suggested that dust growth in the cold gas phase dominates the dust abundance in elliptical galaxies while dust is efficiently destroyed in the hot X-ray emitting plasma (hot gas). In order to understand the dust evolution in elliptical galaxies, we construct a simple model that includes dust growth in the cold gas and dust destruction in the hot gas. We also take into account the effect of mass exchange between these two gas components induced by active galactic nucleus (AGN) feedback. We survey reasonable ranges of the relevant parameters in the model and find that AGN feedback cycles actually produce a variety in cold gas mass and dust-to-gas ratio. By comparing with an observational sample of nearby elliptical galaxies, we find that, although the dust-to-gas ratio varies by an order of magnitude in our model, the entire range of the observed dust-to-gas ratios is difficult to be reproduced under a single parameter set. Variation of the dust growth efficiency is the most probable solution to explain the large variety in dust-to-gas ratio of the observational sample. Therefore, dust growth can play a central role in creating the variation in dust-to-gas ratio through the AGN feedback cycle and through the variation in dust growth efficiency.

1. Introduction

In the nearby Universe, elliptical galaxies are known to have less gas, dust, and ongoing star formation activity than spiral galaxies. Yet, they still have some amount of interstellar gas in the form of hot X-ray-emitting halo gas (e.g., O'Sullivan et al., 2001) and cold gas (e.g., Wiklind et al., 1995). Moreover, dust is detected for a significant fraction of elliptical galaxies by optical extinction (e.g., Goudfrooij et al., 1994; van Dokkum and Franx, 1995; Ferrari et al., 1999; Tran et al., 2001) or far-infrared (FIR) emission (e.g., Knapp et al., 1989; Smith et al., 2012; di Serego Alighieri et al., 2013). Dust mass is estimated from the reddening in the optical or from FIR dust emission, and ranges from $\sim 10^4$ to $\sim 10^7\,M_\odot$ (e.g., Goudfrooij et al., 1994; Leeuw et al., 2004). Since the existence of dust could affect the cooling and chemical processes (Dwek, 1987; Fabian et al., 1994; Voit and Donahue, 1995; Seok et al., 2015; Hirashita et al., 2015), the understanding of the origin and evolution of dust in elliptical galaxies is important in clarifying their evolution.

Because the stellar population is dominated by old stars whose ages are comparable to the cosmic age, the dust in elliptical galaxies is predominantly supplied by asymptotic giant branch (AGB) stars rather than by supernovae. However, dust destruction by sputtering in the X-ray emitting plasma is so efficient that the observed dust mass cannot be explained by the balance between the supply from AGB stars and the destruction (e.g., Patil et al., 2007). Thus, some authors argue that the dust existing in elliptical galaxies is possibly injected from outside via the merging or accretion of external galaxies (Forbes, 1991; Temi et al., 2004; Fujita et al., 2013). The lack of correlation between dust FIR luminosity and stellar luminosity is also taken as evidence of external origin of dust (Temi et al., 2007); however, this argument may not hold if dust is processed by mechanisms unrelated to stars.

Recently, Hirashita et al. (2015) have proposed that the existence of dust in elliptical galaxies can be explained by dust growth by the accretion of gas phase metals in the cold interstellar medium (ISM). They also suggest that the presence of dust growth also explains the extinction curves observed in elliptical galaxies. The dust-to-gas ratio could become as high as $\gtrsim 10^{-3}$ by accretion, explaining the high dust abundance in some elliptical galaxies. However, dust growth in the cold gas has not been considered as a major source of dust in the context of dust evolution in elliptical galaxies. Dust growth has already been noted as a major mechanism of dust mass increase in a wide context of galaxy evolution (e.g., Dwek, 1998; Hirashita, 1999; Inoue, 2003; Zhukovska et al., 2008, 2016; Valiante et al., 2011; Mattsson and Andersen, 2012; Mancini et al., 2015; Popping et al., 2016; Hou et al., 2016), and some experimental studies have also shown that dust grains could grow by accreting the gas-phase metals (Rouillé et al., 2014; but see Ferrara et al., 2016). Thus, constructing a dust evolution model that includes this dust growth mechanism would contribute to the understanding of

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dust evolution in elliptical galaxies.

The overall evolution of dust should be considered in relation to the gas evolution, especially because gas and dust are usually dynamically coupled on galactic scales. Recent studies have proposed that the gas cooling in galaxies is strongly regulated by the energy input from active galactic nuclei (AGNs). The energy input from AGN winds (Silk and Rees, 1998; Fabian, 1999; King, 2005) or AGN jets (Wagner and Bicknell, 2011; Mukherjee et al., 2016) prevents cooling flows from occurring and/or makes cold gas evaporate (see also Ciotti and Ostriker, 2001; Fabian, 2012). These kinds of energy input are called AGN feedback, and are considered to play an important role in galaxy formation and evolution (Croton et al., 2006; Booth and Schaye, 2009).

Temi et al. (2007) showed the existence of a dust emission component extended over 5–10 kpc in elliptical galaxies using the *Spitzer* 70 μm band data. They suggest that this cold dust component was originally contained in the cold gas, which was then heated by AGN feedback and eventually mixed with the hot gas. In their scenario, the heated gas is transported into the hot gas by buoyant force, and the time-scale of the transport is around 10^7 yr. Kaneda et al. (2011) also showed in an elliptical galaxy (NGC 4125) a dust emission component whose extension is similar to the distribution of the hot X-ray emitting halo. The multi-phase structures and irregular morphologies of X-ray emitting hot plasmas could be explained by bubbles created by AGN feedback (Buote et al., 2003).

A part of the hot gas may cool down to reform the cold gas, which could contribute to the fueling of AGN (Werner et al., 2014). AGN feedback may compress the surrounding gas and enhance gas cooling locally (Valentini and Brighenti, 2015). Because dust grains can grow in the cold gas as mentioned above, the cold gas injected into the hot gas by AGN feedback would supply the dust to the hot gas. This dust supply could be dominant over the dust production by AGB stars. If so, formation of cold gas and the subsequent AGN fueling leading to AGN feedback play a dominant role in the dust evolution in elliptical galaxies.

If the dust evolution is affected by episodic AGN activities, which appear as a result of a cycle of gas ejection and cooling, the statistical properties of the dust abundances in elliptical galaxies are determined by the time-scales of dust processing relative to the period of an AGN cycle. Lauer et al. (2005) inferred the period of an AGN cycle in early-type galaxies based on the dust lifetime against sputtering in the hot gas and the fraction of dust detection for a sample, obtaining a period of $\sim 10^8$ yr. The dust contained in the cold gas may be injected into the hot gas in an episodic way associated with the AGN cycle, if AGN feedback efficiently heats the cold gas (Mathews et al., 2013).

In this paper, we make a theoretical model of dust evolution in AGN feedback cycles by including important physical processes such as the mass exchange between the hot and cold gas components and the dust evolution in those gases. For dust processing, we consider dust destruction by sputtering in the hot gas and dust growth by the accretion of gas-phase metals in the cold gas. This modeling enables us to examine how AGN feedback cycles affect the dust abundances in elliptical galaxies. We can also examine the effect of dust growth on the dust abundance in elliptical galaxies for the first time.

The paper is organized as follows: we formulate the model of dust evolution in an elliptical galaxy in Section 2. We show the results in Section 3. We discuss the model predictions, and compare them with observational data in Section 4. Finally we conclude in Section 5.

2. Model

We construct a model that describes the dust evolution in an elliptical galaxy. For dust sources, in addition to AGB stars considered in previous studies (Mathews and Brighenti, 2003; Patil et al., 2007), we also consider dust supply from the cold gas where dust grows by the accretion of gas-phase metals. The dust in the cold gas is injected into the hot gas by AGN feedback together with the cold gas. The dust injected into the hot gas is destroyed by sputtering. The hot component ($\sim 10^7$ K) is the gas whose temperature is comparable to the virial temperature determined by the global gravitational potential of the elliptical galaxy while the cold component is cold and dense enough to host dust growth ($\lesssim 100$ K; Hirashita et al., 2015). To make the model as simple as possible, we treat each gas component as a single zone and consider the mass exchange between the two components. Dust growth and destruction are treated consistently with the evolution of each gas component as explained below.

2.1. Basic equations

We consider the mass exchange between the hot and cold phases. The evolution of the cold gas mass $M_{\rm g,c}$ as a function of time t is written as

$$\frac{dM_{\rm g,c}}{dt} = \dot{M}_{\rm in} - \dot{M}_{\rm ret}, \tag{1}$$

where $\dot{M}_{\rm in}$ is the infall rate of the cooled gas and $\dot{M}_{\rm ret}$ is the gas return rate from the cold to the hot phase by AGN feedback. These two terms are modeled below.

The hot gas is treated as a constant reservoir of gas for simplicity; that is, we assume that the mass of hot gas, $M_{\rm g,h}$ is constant ($dM_{\rm g,h}/dt = 0$). This treatment neglects the complication arising from the possibility that there could be a supply/loss of hot gas from/to outside. Because the hot gas basically acts as an efficient destroyer of dust regardless of the choice of $M_{\rm g,h}$, the value of $M_{\rm g,h}$ has a minor influence on the results compared with other parameters. However, we should note that the dust-to-gas ratio in the hot gas is directly affected by $M_{\rm g,h}$ since it directly enters the dust-to-gas ratio in the hot gas. We discuss the value of $M_{\rm g,h}$ again in Section 2.3.

The time evolution of the dust mass in the cold phase, $M_{\rm d,c}$, is written as

$$\frac{dM_{\rm d,c}}{dt} = \mathcal{D}_{\rm h}\dot{M}_{\rm in} - \mathcal{D}_{\rm c}\dot{M}_{\rm ret} + \frac{M_{\rm d,c}}{\tau_{\rm grow}}, \tag{2}$$

where $\mathcal{D}_{\rm h} \equiv M_{\rm d,h}/M_{\rm g,h}$ and $\mathcal{D}_{\rm c} \equiv M_{\rm d,c}/M_{\rm g,c}$ are the dust-to-gas ratios in the hot and cold phases, respectively ($M_{\rm d,h}$ and $M_{\rm d,c}$ are the dust mass in the hot and cold gas, respectively), and $\tau_{\rm grow}$ is the time-scale of dust growth by the accretion of gas-phase metals in the cold gas. The dust growth timescale $\tau_{\rm grow}$ is given in Section 2.3 (Eq. (9)), and is treated as a function of $\mathcal{D}_{\rm c}$. The time evolution of the dust mass in the hot phase, $M_{\rm h,c}$, on the other hand, is written as

$$\frac{dM_{\rm d,h}}{dt} = -\mathcal{D}_{\rm h}\dot{M}_{\rm in} + \mathcal{D}_{\rm c}\dot{M}_{\rm ret} - \frac{M_{\rm d,h}}{\tau_{\rm sput}} + \mathcal{D}_{\rm AGB}\alpha M_{*}, \tag{3}$$

where $\tau_{\rm sput}$ is the dust destruction time-scale by sputtering in the hot gas, $\mathcal{D}_{\rm AGB}$ is the dust-to-gas ratio in AGB star winds, α is the mass loss rates of AGB stars per stellar mass, and M^* is the total stellar mass (αM_* is the total mass loss rate of AGB stars). Using $M_{\rm d,c} = \mathcal{D}_{\rm c}M_{\rm g,c}$, $M_{\rm d,h} = \mathcal{D}_{\rm h}M_{\rm g,h}$, and Eq. (1), we rewite Eqs. (2) and (3) as the following equations for the dust-to-gas ratios:

$$\frac{d\mathcal{D}_{\rm c}}{dt} = \frac{\mathcal{D}_{\rm c}}{\tau_{\rm grow}} + (\mathcal{D}_{\rm h} - \mathcal{D}_{\rm c})\frac{\dot{M}_{\rm in}}{M_{\rm g,c}}, \tag{4}$$

$$\frac{d\mathcal{D}_{\rm h}}{dt} = -\mathcal{D}_{\rm h}\frac{\dot{M}_{\rm in}}{M_{\rm g,h}} - \frac{\mathcal{D}_{\rm h}}{\tau_{\rm sput}} + \mathcal{D}_{\rm c}\frac{\dot{M}_{\rm ret}}{M_{\rm g,h}} + \mathcal{D}_{\rm AGB}\frac{\alpha M_{*}}{M_{\rm g,h}}. \tag{5}$$

We solve Eqs. (1), (4) and (5). Below we formulate some undetermined terms and estimate a reasonable range for each parameter (Table 1).

2.2. Mass exchange between the phases

The mass exchange between the cold and hot phases is described by $\dot{M}_{\rm in}$ (inflow of cooled hot gas to the cold gas) and $\dot{M}_{\rm ret}$ (return of cold gas