Cosmological simulation with dust evolution

Kuan-Chou Hou[1,2], Shohei Aoyama[1], Hiroyuki Hirashita[1], Kentaro Nagamine[3,4], Ikkoh Shimizu[3,5]

[1]*Academia Sinica, Taiwan,* [2]*National Taiwan University, Taiwan,* [3]*Osaka University, Japan,*
[4]*University of Nevada, USA,* [5]*Osaka Sangyo University, Japan*

Dust enrichment is one of the most important aspects in galaxy evolution. The evolution of dust is tightly coupled with the nonlinear evolution of the interstellar medium (ISM) , mainly driven by star formation and stellar feedback, which lead to the chemical enrichment in a galaxy. Numerical hydrodynamical simulation provides a powerful approach to studies of such nonlinear processes.

In this work, we perform a cosmological simulation using smoothed particle hydrodynamics (SPH) simulation in which dust evolution is implemented. We consider dust production in stellar ejecta, destruction in supernova shocks, dust growth by accretion and coagulation, and dust disruption by shattering and thermal sputtering for the processes driving the dust evolution. We also treat the evolution of grain sizes distribution by representing the entire grain radius range by small and large grains (divided at $\sim$0.03 μm).

We show that our cosmological simulation allows us to analyze the dust abundance and dust properties, such as dust-to-gas mass ratio ($\mathcal{D}$), dust-to-stellar mass ratio ($M_{\rm d}/M_*$) and small-to-large grain abundance ratio ($\mathcal{D}_{\rm s}/\mathcal{D}_{\rm l}$), in galaxies statistically. Besides, we also examine the redshift evolution of dust content in galaxies. In particular, we show how the relation between dust abundance and galaxy properties evolves as a function of redshift (z).

The relation between dust-to-gas ratio and metallicity ($\mathcal{D}$–Z relation) at $z = 0$, predicted in our simulation is consistent with observations of the nearby galaxies. We also reproduced the nonlinearity of the $\mathcal{D}$–Z relation. The most important process for this nonlinearity is dust growth by accretion, which imprints a characteristic metallicity above which the increase of $\mathcal{D}$ as a function of Z becomes steeper. At $z > 0.5$, because the time-scale of chemical enrichment is shorter, the turning point in the $\mathcal{D}$–Z relation shifts to higher metallicities. Since the metallicity has a tight correlation with the stellar mass (M_*), $\mathcal{D}$ also correlates with the stellar mass, and the above nonlinear turning point shifts to higher stellar mass with increasing redshift. The dust-to-stellar mass ratio $M_{\rm d}/M_*$ has a peaks around $M_* \sim 3 \times 10^{10}\ M_\odot$ and decreases toward both high and low mass ends. At the low mass end, $M_{\rm d}/M_*$ increases significantly from high to low redshift. This is interpreted as down-sizing of dusty objects. $\mathcal{D}$ and $M_{\rm d}/M_*$ have correlation with the specific star formation rate (sSFR) which has a dependence on stellar mass and metallicity. In the local universe, $\mathcal{D}$ decreases with increasing sSFR, however, at high redshift, high-$\mathcal{D}$ galaxies have intermediate sSFR with low-$\mathcal{D}$ galaxies having a wide scatter in sSFR. For the grain size, results show that galaxy with higher Z (or M_*) has higher $\mathcal{D}_{\rm s}/\mathcal{D}_{\rm l}$, and that $\mathcal{D}_{\rm s}/\mathcal{D}_{\rm l}$ increases continuously from high to low z as small grains are produced by interstellar processing. We also discuss dust enrichment in the intergalactic medium (IGM) driven by feedback processes. In the IGM, $\mathcal{D}$ remains as low as $< 10^{-3.5}$, and $\mathcal{D}_{\rm s}/\mathcal{D}_{\rm l}$ is also low. The dominance of large grains indicates that most of the IGM dust was ejected from galaxies before being processed in the ISM.

Our predictions on the dust content in high-redshift galaxies can be tested by ALMA and future observations.