Galaxies at High Redshift and Their Evolution Over Cosmic Time
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Metallicities in cosmological simulations with AGN feedback

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Abstract. In our cosmological, chemodynamical simulations, (i) the black hole mass–velocity dispersion relation does not evolve, and black holes actually grow along the relation. (ii) the stellar mass–metallicity relation does not change its shape, while the gas-phase relation has a steeper slope at higher redshifts. (iii) While stellar metallicity gradients are made shallower by galaxy mergers, gas-phase gradients are affected more strongly by AGN feedback.

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Our simulations include star formation, chemical enrichment, and feedback from supernovae (Kobayashi, Springel, & White 2007) and from active galactic nuclei (AGN) (Taylor & Kobayashi 2014). Different from previous works, our black holes are not the products of galaxy mergers but originate the first stars. Our AGN feedback helps producing the down-sizing phenomena (Taylor & Kobayashi 2015a), and causes metal-enhanced outflows, which transport metals into the circumgalactic medium and the intergalactic medium (Taylor & Kobayashi 2015b). Nonetheless, the metallicity changes of galaxies are negligible, and the mass–metallicity relations (MZRs), which are mainly generated by supernova feedback at the first star burst, are preserved. The present MZRs of simulated galaxies, which are in good agreement with various observations, both for gas-phase abundances and stellar populations. We show the time evolution of these MZRs in Figure 1. The stellar MZR does not change its shape, but the metallicity significantly increases from $z \sim 2$ to ~ 1, while the gas-phase MZR does change shape, having a steeper slope at higher redshifts ($z \lesssim 3$). Within galaxies, metallicity radial gradients are produced. We find a weak correlation between the gradients and galaxy mass, which is consistent with available observations. Stellar metallicity gradients are found to be made shallower by galaxy mergers, and are generally shallower in denser environments, regardless of galaxy mass. On the other hand, gas-phase metallicity gradients are affected more strongly by AGN feedback in massive galaxies, and stellar feedback in low-mass galaxies.

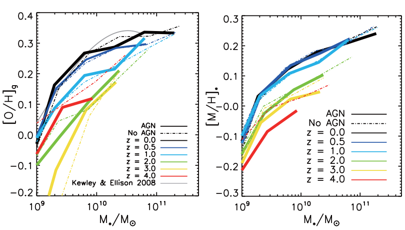

Figure 1. Time evolution of mass-metallicity relations for gas (left panel, SFR weighted) and stars (right panel, V-band luminosity weighted) from $z = 0$ to 5. Solid (dot-dashed) lines correspond to the simulation with (without) AGN feedback.

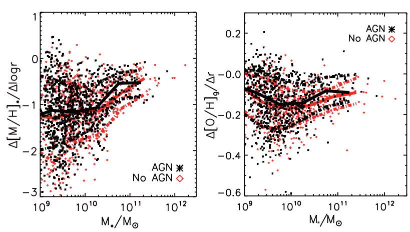

Figure 2. Gas-phase (left panel) and stellar (right panel) metallicity radial gradients as a function of galaxy mass at $z = 0$ in the simulation with (black stars) and without (red diamonds) AGN. Solid and dot-dashed lines show the median and 1σ trends, respectively.