論文の内容の要旨

Spectroscopic Study on Galactic Outflows over Cosmic History
(宇宙史における銀河アウトフローの分光学的研究)

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The galactic outflows in star-forming galaxies are thought to play a key role to regulate the galaxy evolution. Despite many observations in a wide redshift range, it is unclear how the outflows evolve throughout redshifts. We conduct a systematic study of the galactic-scale cool/warm outflows in star-forming galaxies at $z \sim 0$–6, by analyzing the metal absorption lines in the observed-frame optical spectra taken from the SDSS DR7 at $z \sim 0$, the DEEP2 DR4 at $z \sim 1$, Keck galaxies in Erb et al. at $z \sim 2$, and Lyman break galaxies in Capak et al. at $z = 5$–6. We carefully construct galaxy samples with similar stellar-mass distributions at $z \sim 0$, 1, 2, and 5–6 and produce composite spectra with high signal-to-noise ratio to perform the multi-component fitting of absorption-line profiles and stellar continua to the absorption lines. We finally obtain outflow properties from the blueshifted outflow components.

We measure the maximum ($v_{\rm max}$) and central ($v_{\rm out}$) outflow velocities from the outflow components. By making use of the ALMA [C II]158 μm emission lines for systemic velocities, we can present the first measurements of the outflow velocities at $z = 5$–6: $v_{\rm max} = 700^{+180}_{-110}$ km s^{-1} and $v_{\rm out} = 400^{+100}_{-150}$ km s^{-1}. Although the available absorption lines depend on the redshifts, we investigate the redshift evolution of the outflow velocities by comparing the absorption lines that have similar ionization energy and line depth at different redshifts (Na I D and Mg I at $z \sim 0$–1; Mg II and C II at $z \sim 1$–2). This comparison shows no significant differences between the outflow velocities derived from the low to high-ionization absorption lines. We identify, for the first time, the $v_{\rm max}$ value of our $z = 5$–6 galaxies is 3.5 times higher than those of $z \sim 0$ galaxies and comparable to $z \sim 2$ galaxies at a fixed stellar mass of $M_* \sim 10^{10.1}$ $M_\odot$. This implies that the outflow velocities strongly increase from $z \sim 0$ to 2 and weakly increase from $z \sim 2$ to 6 at the fixed stellar mass.

Estimating the halo circular velocity $v_{\rm cir}$ from the stellar masses and the abundance matching results, we investigate a $v_{\rm max}$–$v_{\rm cir}$ relation. The maximum outflow velocity $v_{\rm max}$ for galaxies with

$M_* = 10^{10.0-10.8}$ $M_\odot$ shows a tight positive correlation with $v_{\rm cir}$ and the galaxy star formation rate (SFR) over $z = 0$–6 with a small scatter of $\simeq \pm 0.1$ dex. This positive correlation between $v_{\rm max}$ and $v_{\rm cir}$ is in good agreement with theoretical predictions by numerical simulations. This suggests that the outflow velocity is physically related to the halo circular velocity. The redshift evolution of $v_{\rm max}$ at fixed M_* can be explained by the increase of $v_{\rm cir}$ toward high redshift.

To find the fundamental parameter to determine $v_{\rm max}$ with a single relation throughout all redshifts, we study relations between $v_{\rm max}$ and galaxy properties. The outflow maximum velocity $v_{\rm max}$ shows strong correlations with $v_{\rm cir}$, SFR, SFR/M_*, and the predicted SFR surface density $\Sigma_{\rm SFR}$. In addition to the tight correlations, only $v_{\rm cir}$ and SFR can explain $v_{\rm max}$ with single scaling relations throughout $z = 0$–6. Therefore, $v_{\rm cir}$ or SFR is likely to be the fundamental parameter.

We also estimate the mass loading factor (η), a ratio of the mass outflow rate to SFR, under the assumption of the fiducial parameters. We find that the η value increases from $z \sim 0$ to 2 by $\eta \propto (1+z)^{1.2\pm0.3}$ at a given $v_{\rm cir}$, albeit with a potential systematics caused by model parameter choices. The redshift evolution of $v_{\rm max}$ ($v_{\rm out}$) and η is consistent with the galaxy-size evolution and explained by high-gas fractions in high-redshift massive galaxies, which is supported by radio observations. We obtain a scaling relation of $\eta \propto v_{\rm cir}^{a}$ for $a = -0.2 \pm 1.1$ in our $z \sim 0$ galaxies that agrees with the momentum-driven outflow model ($a = -1$) within the uncertainty.

We indirectly estimate the escape fraction of the Lyman-continuum photons using absorption-line profiles. Our measurement at $z = 5$–6 is located on the relation found at $z \sim 2$–4 between the maximum covering fraction of the Si II line and the Lyα equivalent width. The intrinsic Lyman-continuum escape fraction would be much lower than 20%, while the ratio absorption-line profile exhibits a signature comparable to the local Lyman-continuum leaking galaxies.