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Galactic outflows in star-forming galaxies at $z \sim 6$ studied with deep UV spectra and ALMA emission line

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Abstract. We present a velocity of galactic outflows in star-forming galaxies at the highest redshift, $z \sim 6$, so far studied with metal absorption lines. Absorption-line studies of galactic outflows need well-determined redshifts, but there are few strong emission lines in the observed-frame optical spectra of galaxies at high redshifts. In this work, we use the systemic redshifts determined by the ALMA [CII]158 μm emission lines. The sample consists of seven Lyman break galaxies at $5.1 < z < 5.7$ whose Keck/DEIMOS and ALMA data are available in the archive. The outflow maximum velocity ($v_{\rm max}$) is estimated by a fitting of line profiles to metal absorption lines in a composite spectrum. We find that $v_{\rm max}$ monotonically increases from $z \sim 0$ to 6 and that $v_{\rm max}$ tightly correlates with the halo circular velocity estimated from the stellar mass.

Keywords. galaxies: evolution, galaxies: high-redshift, galaxies: kinematics and dynamics

1. Introduction

Galactic outflows in star-forming galaxies are thought to play an important role in regulating the galaxy and IGM evolution (Somerville & Davé 2015). Recently, deep optical spectra in the observed frame enable us to probe gas kinematics in high-redshift galaxies using metal absorption lines. Sugahara *et al.* (2017) show that the outflow velocity increases from $z \sim 0$ to 2 in galaxies with similar stellar mass and star formation rate (SFR) ranges. An important parameter to measure the outflow velocity is the precise systemic redshifts. This makes it difficult to study the outflows at $z > 2$ because there are few strong emission lines in the rest-frame FUV spectral bands. Here, we present the outflow velocity of galaxies at $z \sim 5$–6 measured with absorption lines in deep rest-frame FUV spectra, using the systemic redshifts determined by ALMA [CII] 158 μm observations.

2. Redshift Evolution of Outflow Maximum Velocity

The sample consists of seven Lyman break galaxies at $z = 5$–6 observed by DEIMOS on the Keck telescope (PI: P. Capak). Their systemic redshifts have been already determined by ALMA [CII] 158 μm observations (Capak *et al.* 2015). We stack the DEIMOS spectra

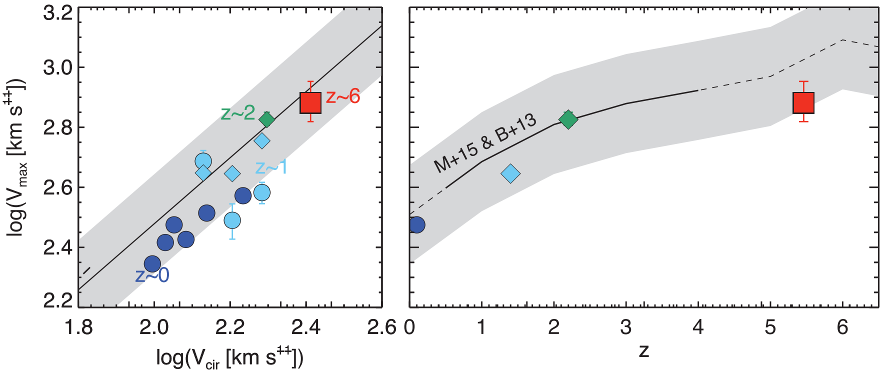

Figure 1. Left: $v_{\rm max}$ as a function of $v_{\rm cir}$. The red square is a result of this work. The data points at $z \sim 0$ (blue), $z \sim 1$ (cyan), and $z \sim 2$ (green) are presented by Sugahara *et al.* (2017). The solid line is a relation given by Muratov *et al.* (2015). Right: redshift evolution of $v_{\rm max}$ at $\log M_* \sim 10^{10.3}\ M_\odot$. The symbols are the same as in the left panel. The line indicates a relation based on Muratov *et al.* (2015) and Behroozi *et al.* (2013). The 25th and 75th percentile of the relations are indicated by the shaded region.

to obtain a composite rest-frame FUV spectrum based on the systemic redshifts, fitting a line profile to the Si II λ1260 and C II λ1335 absorption lines, simultaneously. From the best-fit parameters, the outflow maximum velocity $v_{\rm max}$ is defined as a velocity at which the flux density becomes 90% of the continuum from the bottom of the absorption line.

The measured value is $v_{\rm max} = 760^{+140}_{-100}$ km s^{-1}. We compare $v_{\rm max}$ at $z = 5$–6 with the velocities at $z \sim 0$–2 presented in Sugahara *et al.* (2017). Note that the value at $z \sim 2$ is re-calculated in the manner of this work. The $v_{\rm max}$ value at $z = 5$–6 is higher than the velocities at $z \sim 0$ and 1 and comparable to the one at $z \sim 2$. In the left panel of Figure 1, $\log v_{\rm max}$ is compared with the halo circular velocity $\log v_{\rm cir}$ that is converted from the stellar mass using the stellar-to-halo mass ratio given by Behroozi *et al.* (2013). Over $z \sim 0$–6, $v_{\rm max}$ has a tight correlation with $v_{\rm cir}$. In addition, interestingly, our measurements are in good agreement with the prediction of $v_{\rm max} \propto v_{\rm cir}^{1.1}$ about the hot outflows by the FIRE simulation (Muratov *et al.* 2015). This suggests that $v_{\rm max}$ physically connects with $v_{\rm cir}$ and that the cold outflows are associated with the hot outflows. In the right panel of Figure 1, $v_{\rm max}$ is plotted as a function of the redshift at the fixed stellar mass of the $\log M_* \sim 10^{10.3}$ M$_\odot$. The figure shows a monotonic increase in $v_{\rm max}$ with increasing redshift, including a large increase from $z \sim 0$ to 2 and a small increase from $z \sim 2$ to 6. This evolution is explained by a combination of the linear $v_{\rm max}$–$v_{\rm cir}$ relation and the redshift evolution of $v_{\rm cir}$. Because the halo mass does not significantly change around $\log M_* \sim 10^{10.3}$ M$_\odot$ (Behroozi *et al.* 2013), $v_{\rm cir}$ changes along with the halo radius $r_{\rm h}$. Thus, the $v_{\rm max}$ evolution is expressed as $v_{\rm max} \propto v_{\rm cir} \propto r_{\rm h}^{-0.5} \propto (1+z)^{0.5}$.

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