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Metallicity of the high-redshift Universe traced by radio galaxies

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Abstract. We investigate the metallicity of the narrow line regions (NLRs) of high-z radio galaxies (HzRGs), using new deep optical spectra of 9 HzRGs obtained with FORS2 on VLT and data from the literature. To estimate the metallicity of NLRs we focus on the CIV/HeII and CIII]/CIV flux ratios. Based on comparison between the observed emission-line flux ratios and the prediction of our photoionization model calculations, we find no significant metallicity evolution in NLRs of HzRGs, up to $z \sim 4$. We discuss the possibility that massive galaxies had almost completed the major epoch of the star formation in the very high-z universe ($z > 5$).

Keywords. galaxies: active, galaxies: evolution, quasars: emission lines, quasars: general

1. Introduction

Metallicity of galaxies is one of the most important aspects to understand the formation and evolution of galaxies, since it is closely related with the past star formation history of galaxies. The most straightforward way to investigate chemical evolution of galaxies is by measuring the metallicity of galaxies at various redshifts and exploring the systematic trends in the metallicity as a function of redshift (see Maiolino *et al.* 2008 and references therein).

An approach to study the metallicity of galaxies in high-z universe is to focus on active galactic nuclei (AGNs). AGNs generally show various emission lines in rest-frame ultraviolet to infrared wavelengths. Here we focus on the rest-frame ultraviolet lines, since we can easily measure the emission-line fluxes of high-z AGNs by means of optical spectroscopic observations. Now we focus on the narrow-line region (NLR) of high-z radio galaxies (HzRGs) which is a good tracer of chemical properties in the spatial scale of their host galaxies.

Some studies of the NLR metallicity of HzRGs have already been carried out by studying the emission-line flux ratios of NV/CIV and NV/HeII. However, the emission-ine flux of NV in HzRGs is generally too faint, especially for metal-poor gas. Nagao *et al.* (2006) proposed a new metallicity diagnostic diagram with the CIV, HeII, and CIII] emission lines, all of which are moderately strong in the rest-frame UV spectra of HzRGs, even at low metallicities. They studied the NLR metallicity of HzRGs and reported that the observational data do not show any evidence of significant evolution in the gas metallicity of NLRs within the redshift range $1.2 < z < 3.8$. We note, however, that their sample included only 5 objects at $z > 2.7$. Thus, observing more HzRGs at this redshift range is crucial to assessing the possible metallicity evolution.

We present new spectroscopic observations of 9 HzRGs at $2.7 < z < 3.5$. By combining the new data with the Nagao *et al.* (2006) database, we discuss the chemical evolution of HzRGs in the whole $z \sim 1 - 4$ redshift range.

2. Observations and photoionization models

We observed 9 HzRGs at $z > 2.7$ with FORS2 at the VLT (Very Large Telescope). We obtained emission-line fluxes of CIV, HeII, and CIII] for all targets. We combine our new spectra with data from Nagao *et al.* (2006), which include these emission-line fluxes of 48 HzRGs at $1.2 < z < 3.8$ (included only 5 objects at $z > 2.7$). Finally, we get 57 HzRGs at $1.2 < z < 3.8$ including 14 objects at $z > 2.7$ (or 6 object at $z > 3.0$).

To infer the metallicity from the observed emission-line spectra, we carried out model calculations using Cloudy version 07.02 (Ferland et al. 1998). We assumed that the clouds in the NLR of HzRGs are mainly photoionized and not significantly affected by shocks. Nagao *et al.* (2006) demonstrated that this assumption is appropriate when focusing on CIV, HeII, and CIII] (see also Matsuoka *et al.* 2009). In Fig. 1, the results of our photoionization model calculations are plotted with solid and dashed lines.

3. Discussion

By comparing the observed flux ratios of HzRGs with the prediction of photoionization models, we investigate the gas metallicity. In Fig. 1, we plot the flux ratios of HzRGs on the diagnostic diagram with the calculated model grids. Although 9 new data are at higher redshift than the data in Nagao *et al.* (2006) on average, there is no systematic difference in the data distribution between our new observations and the data of Nagao *et al.* (2006). This result naively suggests that there is no significant chemical evolution in NLRs of HzRGs, even up to $z \sim 4$. If the minimum timescale for a significant enrichment of carbon ($\sim$ 0.5 Gyr) is take into account, the major epoch of the star formation in HzRGs may have occurred at $z > 5$. If the host galaxies of HzRGs are very massive, this scenario implies that massive galaxies had almost completed the major epoch of the star formation at $z > 5$ (see Matsuoka *et al.* 2009 for more details).

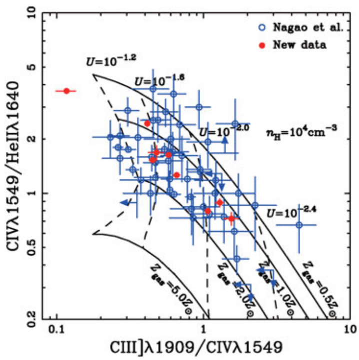

Figure 1. The flux ratios of HzRGs and calculated model grids plotted on the diagnostic diagram of CIV/HeII versus CIII]/CIV. Our new data are shown with red-filled circles, while the data compiled by Nagao *et al.* (2006) are shown with blue-open circles and arrows. Constant metallicity and constant ionization parameter sequences are denoted by solid and dashed lines, respectively. These models are calculated by adopting $n_{\rm H} = 10^4$ cm^{-3} (a typical NLR density).

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