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Multiple Absorption Systems in the Lines of Sight to Quadruply Lensed Quasar H1413+1143 As a Probe of the Circumgalactic medium around Dwarf Galaxy

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Abstract. We present the first measurement of differences in MgII absorption strength in multiple intervening absorbers, which are also identified as (sub-)Damped Lyman alpha absorption systems, in the four spectra of the quadruply lensed quasar H1413+1143, often referred to the "Cloverleaf", from highly spatial resolution and high signal-to-noise spectroscopy with an optical multi-mode spectrograph, the Kyoto tridimentional spectrograph II on board the Subaru telescope. The detection of significant MgII absorptions in multiple components in the spatially-resolved spectra suggests that chemical enrichment differs at least on scale of about 10 kpc within the separation of sightlines. For, a DLA system at redshift $z_{\rm abs} = 1.66$, the rest equivalent widths of MgII absorption lines change by factors up to 6, which is similar to those of HI absorption lines. This suggests that (inhomogeneous) cold absorbers which give rise to strong HI/MgII absorptions dwell on a scale within 10 kpc in the circumgalactic medium (CGM).

Keywords. galaxies: evolution, intergalactic medium, quasars: absorption lines

1. Introduction

A crucial aspect of understanding formation and evolution of dwarf galaxy is exchange of gas and metals between dwarf galaxy and the circumgalactic medium (CGM) via galactic outflow and/or inflow. A powerful tool to investigate the CGM is often provided by absorption-line systems found in quasar spectra, the so called 'quasar absorption systems'. The formation and evolution processes of dwarf galaxies depend sensitively on the physical and chemical conditions of the CGM since the shallow gravitational potential of dwarf galaxies allows to produce gas/metal flows not only in the halo but also in the circumgalactic region beyond the virial radius. The quasar absorption systems

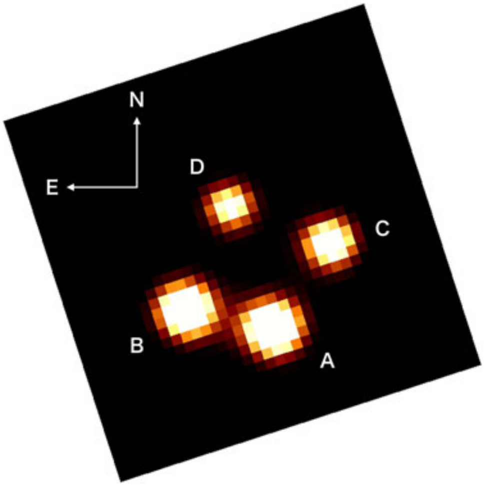

Figure 1. The spatially-resolved image of H1413+1143 using the Kyoto3DII.

offer valuable opportunities to explore the detailed spatial distributions of neutral gas and metals around dwarf galaxies, the dynamics of gas and metals around the halos, and so on.

In particular, Damped Lyman α (DLA) absorption system (the HI column densities $N_{\rm HI}/{\rm cm}^{-2} > 10^{20.3}$) is known to trace dwarf galaxies based on the optical/UV counterpart survey. At redshift $z < 2$, the optical/UV counterparts of DLAs show the medians of the star formation rates ~ 1 $M_\odot$ yr^{-1}, the metallicities $\sim -0.5 Z_\odot$ and the impact parameters ~ 10 kpc. Furthermore, a large fractions of DLAs at $z < 2$ also give rise to very-strong MgII absorptions (e.g., Rao *et al.* 2017). Actually, it has been well known that the very-strong MgII system ($W_{\rm r}^0 > 1$ Å) is associated specifically with gas outflow. At $z < 2$, for instance, while an ultra-strong MgII absorption feature shows the signature of cold inflows depositing MgII absorbers, very-strong MgII systems also originate from outflow gas from the host galaxies with velocities $100 - 1000$ km s^{-1} (e.g., Bordoloi *et al.* 2014). This suggests that strong MgII system is a powerful probe of the metal distribution in the CGM where neutral hydrogen gas also produces strong HI absorption. Particularly for dwarf galaxies, large amounts of pristine gas with very-strong MgII systems could still be in the CGM. However, these studies focus on the individual gas-flow signature based on an absorption in the *single* sight-line. Unfortunately, for investigating the spatial structures of galactic flows around dwarf galaxies, there is a quite limited sample size for the CGM producing the *multiple* MgII absorptions due to lack of *multiple* background quasars.

Here, we present the first measurement of differences in multiple MgII absorption strength, which traces metal enrichment in cold gas, in the four separate spectra of the quadruply lensed quasar H1413+1143 from highly spatial resolution and high signal-to-noise spectroscopy with an optical multi-mode spectrograph, the Kyoto tridimentional spectrograph II (Kyoto 3DII) on board the Subaru telescope. The spatially-resolved spectra provides us with multiple intervening absorbers including (sub-) DLAs at absorption redshifts $z_{\rm abs} = 1.66$ and 2.097. The high signal-to-noise spectroscopy with the Kyoto 3DII allows to investigate the spatial extent of metal absorbers in the CGM through the multiple MgII absorption lines ($\lambda\lambda 2796, 2803$) in the spectra toward the multiple background sources.

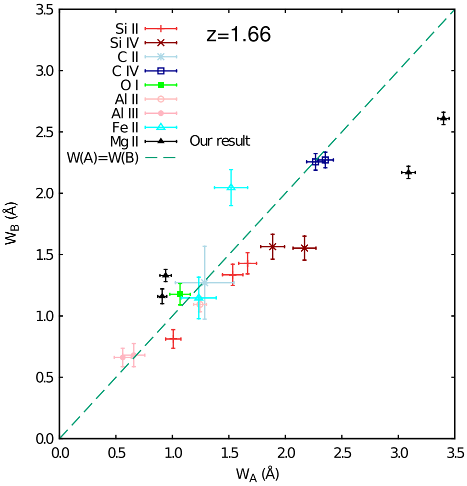

Figure 2. The rest EWs of MgII in comparison to the other metal absorption system at $z_{\rm abs} = 1.66$ in the two spectra in sightlines toward H1413+1143 A and B. Our result for the MgII absorption doublets is shown as data with 1σ errors (*black*).

2. Observation & Results

H1413+1143 at emission redshift $z_{\rm em} = 2.54$, often referred to the "Cloverleaf", has four images by gravitational lensing which all lie within 0.7 arcsec of the center (e.g., Hazard *et al.* 1984; Magain *et al.* 1988).

We observed H1413+1143 on February 8, 2017 with Kyoto3DII optical IFU at a Nasmyth focus of the Subaru telescope (Figure 1). In the IFU (No.5) mode, the field of view (FoV) is about 3.0×3.0 arcsec^2. The total on-source exposure time is 12000 sec (1200 sec $\times 10$). In combination with a 188-element adaptive optics (AO) system, Subaru AO188, we obtained the AO-assisted optical integral-field spectroscopy at wavelength coverage at 6400-9400 Å. The wavelength coverage of the Kyoto3DII spectra allows the first measurement of equivalent widths (EWs) in the separate components for MgII/MgI absorption lines. We successfully found 7 absorption lines in the four spectra toward the spatially-resolved images A/B/C/D of H1413+1143. In the absorption lines, 3 MgII systems are identified at $z_{\rm abs} = 1.66, 2.069, 2.097$.

Here, we focus on the MgII Systems at $z_{\rm abs} = 1.66$. In *all* of the four spatially-resolved spectra toward A/B/C/D components of the background image. We find significantly strong MgII-doublets at $z_{\rm abs} = 1.66$, which consists of two components at $z_{\rm abs} = 1.660$ and 1.664. The system at $z_{\rm abs} = 1.660$ gives rise to the strong MgII absorptions with the rest EWs at $\lambda = 2796, 2803$ Åin the four spatially-resolved spectra toward the A/B/C/D components; $(W_{\rm r}^0(\lambda = 2796\text{Å}),\ W_{\rm r}^0(\lambda = 2803\text{Å}))/\text{Å} = (3.40 \pm 0.05, 3.09 \pm 0.06)$, $(2.61 \pm 0.05, 2.17 \pm 0.05)$, $(2.44 \pm 0.06, 2.19 \pm 0.06)$, $(2.68 \pm 0.07, 2.55 \pm 0.07)$, respectively. The system at $z_{\rm abs} = 1.664$ system also shows strong MgII absorptions in A/B/C/D; $(W_{\rm r}^0(\lambda = 2796\text{Å}),\ W_{\rm r}^0(\lambda = 2803\text{Å}))/\text{Å} = (0.94 \pm 0.05, 0.91 \pm 0.04)$, $(1.33 \pm 0.05, 1.16 \pm 0.06)$, $(0.85 \pm 0.06, 0.93 \pm 0.06)$, $(0.22 \pm 0.06, 0.37 \pm 0.06)$, respectively.

Figure 2 shows the rest EWs of MgII in comparison to the other metal absorption systems at $z_{\rm abs} = 1.66$ in the two spectra in sightlines toward H1413+1143 A and B. This result suggests that the MgII absorption strengths differ from each other toward the component A and B. Previously, Monier *et al.* (1998) investigated the other metal-absorption strengths between the sightlines using the Hubble Space Telescope (HST)

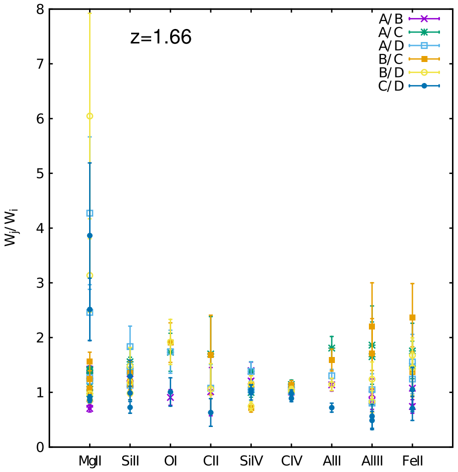

Figure 3. The ratios between the MgII-EWs at $z_{\rm abs} = 1.66$ in four spectra toward the A/B/C/D components of the H1413+1143 images together with those of the other metal absorption lines.

Faint Object Spectrograph, which indicates that the EWs including ones of high-ions (e.g., CIV, SiIV) do not differ from each other.

Figure 3 shows the ratios between the MgII-EWs at $z_{\rm abs} = 1.66$ in four spectra toward the A/B/C/D components together with those of the other metal absorption lines. We find the rest EWs for the six combination of sightlines toward multiple background (A-B, A-C, etc) change by factors up to 6 (for the system at $z = 1.664$), which obviously differs from those of the other metal lines $(0.5 - 3)$.

In HST observation, this system is also identified as a DLA system which exhibits the HI column density $N_{\rm HI} = 6.0 \times 10^{20}$ cm^{-2} in the sightline toward the B component together with strong HI-absorptions toward the other components (Monier *et al.* 2009). The EWs of HI absorption lines change by factors up to 20 in the four sightlines, which is quite similar to those of MgII absorptions in comparison to the observed variations of the other metal absorption strengths. This suggests inhomogeneous spatial distributions of MgII and HI on the four image scales at least within 1.4 arcsec corresponding to the sizes within ~ 10 kpc. The spatial distribution of the multiple absorptions indicates that cold MgII absorbers trace inhomogeneous HI absorbers (DLA systems) on a scale within 10 kpc in the CGM toward H1413+1143.

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