Highly ionized collimated outflow from HE 0238–1904

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ABSTRACT

We present a detailed analysis of a highly ionized, multiphased and collimated outflowing gas detected through O VI, O vi, Ne viii and Mg x absorption associated with the QSO HE 0238–1904 (z_em ≃ 0.629). Based on the similarities in the absorption-line profiles and estimated covering fractions, we find that the O vi and Ne viii absorption trace the same phase of the absorbing gas. Simple photoionization models can reproduce the observed N(Ne viii), N(O vi) and N(Mg x) from a single phase whereas the low-ionization species (e.g. N iii, N iv and O iv) originate from a different phase. The measured N(Ne viii)/N(O vi) ratio is found to be remarkably similar (within a factor of ∼2) in several individual absorption components kinematically spread over ~1800 km s^{-1}. Under photoionization this requires a fine-tuning between hydrogen density (n_H) and the distance of the absorbing gas from the Quasi Stellar Object (QSO). Alternatively, this can also be explained by collisional ionization in hot gas with T ≥ 10^5-7 K. Long-term stability favours the absorbing gas being located outside the broad-line region. We speculate that the collimated flow of such a hot gas could possibly be triggered by the radio jet interaction.

Key words: galaxies: active – quasar: absorption line – quasars: individual: HE 0238–1904.

1 INTRODUCTION

Large-scale outflows from active galactic nuclei (AGNs) play a vital role in regulating star formation in galaxies and the growth of the supermassive black holes at their centres (Silk & Rees 1998; King 2003; Bower et al. 2006). Hence, detecting different forms of outflows is essential to understand the AGN feedback. In the QSO spectrum, outflows can manifest as associated narrow absorption lines (NALs) or broad absorption lines (BALs) in the ultraviolet (UV) and as high-ionization absorption lines and edges (i.e. warm absorbers, W As) in the soft X-ray wavelengths. BALQSOs comprise of ~40 per cent of the total QSO population (Dai, Shankar & Sivakoff 2008) while WAs are detected in the X-ray spectrum of ~50 per cent of Seyfert galaxies (Crenshaw, Kraemer & George 2003) and QSOs (Piconcelli et al. 2005). BALs and NALs are predominantly detected through species with ionization potential (IP) ≤100 eV (e.g. C iv, Si iv and N v), WAs, on the contrary, are identified by species with IP ≥ 0.5 keV (e.g. O vii and O viii). To understand the ionization structure of the outflowing gas entirely it is very important to detect species with intermediate ionization potentials such as O vi (138 eV), Ne viii (239 eV) and Mg x (367 eV). In particular the resonant lines of O viiλ1031, 1037 Ne viiiλ770, 780 and Mg κλ609, 624 are well suited for probing the intermediate physical conditions of the outflowing gas. However, the detections of such species in outflows have been very rare till date.

There are three confirmed and two tentative detections of associated Ne viii (most of them showing radio emission) in the form of narrow absorption lines (UM 675, Hamann et al. 1995; 3C 288.1, Hamann, Netzer & Shields 2000; J2233+066, Petitjean & Srianand 1999; HE 0226−4110, Ganguly et al. 2006 and 3C48, Gupta, Srianand & Saikia 2005) and three QSOs in the form of BAL absorption (Q 0226−1024, Korista et al. 1992; SBS 1542+541, Telfer et al. 1998 and PG 0946+301, Arav et al. 1999). While multiphase photoionization models are generally used to explain these observations (see for example Hamann 1997), the role of collisional ionization is not adequately explored. Here we report the detection of a very strong associated Ne viii (and O vi) absorption in the high-signal-to-noise (S/N) Hubble Space Telescope (HST)/Cosmic Origins Spectrograph (COS) and Far Ultraviolet Spectroscopic Explorer (FUSE) spectra of HE 0238−1904 which has spectral energy distribution (SED) typical of a non-BALQSO. The system is at an ejection velocity of ~4500 km s^{-1} with a kinematic spread of ~2500 km s^{-1}. Along with the Ne viii and O vii absorption, we also detect absorption from N iii, N iv, O iv, O v and Mg x. Throughout this paper we use cosmology with Ω_m = 0.27, Ω_k = 0.73 and H_0 = 71 km s^{-1}Mpc^{-1}.

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2 OBSERVATIONS OF HE 0238–1904

We use HST/COS and FUSE Far-Ultraviolet (FUV) and Near-UV (NUV) spectroscopic observations of HE 0238–1904 that are publicly available in the Multi-mission Archive at Space Telescope (MAST) archive. The FUSE observations were carried out during 2000 December (PI: Moos), 2003 July and 2004 October (PI: Howk). We have downloaded a total of 86 frames calibrated using CALFUSE (v3.2.1) pipeline. The combined spectrum has a resolution of $R \sim 10000$ and S/N of 3–10 pixel$^{-1}$ over the wavelength range 920–1180 Å (Moos et al. 2000; Sahnow et al. 2000). The archived COS observations are from the COS GTO Programme 11541 (PI: Green). These observations consist of G130M and G160M FUV grating integrations at medium resolution of $R \sim 20000$ and S/N $\sim 20–30$ pixel$^{-1}$ in the wavelength range of 1134–1796 Å (Osterman et al. 2011; Green et al. 2012). These spectra and the low-dispersion ($R \sim 3000$) NUV spectra covering the wavelength range of 1650–3200 Å obtained with the G230L COS grating from the archive were extracted using the CALCOS v2.15.4 pipeline. Continuum normalization was done by fitting the regions free of absorption lines with a smooth lower order polynomial.

The optical spectrum of HE 0238–1904 was obtained with the 2-m telescope at IUCAA Girawati Observatory (IGO) on 2011 December 7–8. The long slit spectra (3 x 30 min exposures), covering the wavelength range 3000–9000 Å, were obtained with the GR5 grism of the IUCAA Faint Object Spectrograph (IFOSC) using a slit width of 1.5 arcsec. The raw CCD frames were cleaned and the spectra were extracted using standard IRAF procedures. We use the method explained in Vivek et al. (2009) for removing the fringing at $\lambda > 7000$ Å. The wavelength and flux calibrations were performed using helium–neon lamps and standard star spectrum, respectively. The final co-added spectrum (in the heliocentric frame) has a resolution of $R \sim 300$ and a S/N $\sim 20–40$ pixel$^{-1}$.

2.1 Spectral energy distribution and QSO parameters

From simultaneous Gaussian fits to Hβ, O iii λ4960, 5008 emission lines, we get the emission redshift, $z_{\text{em}} = 0.629 \pm 0.002$. The rest-frame UV/optical SED of HE 0238–1904 is shown in Fig. 1. The (green) star is the X-ray flux calculated from XMM–Newton slew survey data assuming $f_{\text{x}} \propto \nu^{-0.7}$ (Sambruna, Eracleous & Mushotzky 1999) between 0.2 and 2 keV and Galactic $N$(H i) $= 3 \times 10^{20}$ cm$^{-2}$. Consistency of photometric points (purple triangles) of Ojha et al. (2009) with our IGO spectrum (in red) implies a lack of strong flux variability over 4.2 years in the QSO rest frame. This is also supported by the similar UV flux measurements made by COS in 2009 December and Space Telescope Imaging Spectrograph (STIS) G140L in 2002 July. In the absence of strong variability, multiple epoch data can be combined to get the QSO’s SED. Fig. 1 shows that the source is intrinsically brighter in UV than the HST composite spectrum of radio-loud QSOs constructed by Telfer et al. (2002).

We measure X-ray-to-optical spectral index, $\alpha_{\text{ox}} = -1.60$, which is consistent with $\alpha_{\text{ox}} = -1.55$ we get from the measured optical luminosity $L_{\text{ox}} (2500)$ using equation (8) of Stalin et al. (2010). This indicates that HE 0238–1904 is more like a typical non-BAL QSO. The full width at half-maximum (FWHM) of the Hβ line is $\sim 7200$ km s$^{-1}$. Using the prescription of Bentz et al. (2009) we measure the size of the BLR to be $R_{\text{BLR}} \sim 1.1 \times 10^{16}$ cm. This together with the FWHM of Hβ gives a black hole mass of $M_{\text{BH}} = 2.4 \times 10^{10} M_{\odot}$ (Onken et al. 2004) and a Schwarzschild radius of $R_{\text{S}} \sim 7.0 \times 10^{15}$ cm. Following Hall et al. (2011), we find the diameter of the disc within which 90% per cent of the 2700-Å continuum is emitted $D_{2700} \sim 3.2 \times 10^{17}$ cm.

3 ANALYSIS OF THE NE VIII ABSORBER

In Fig. 2 we show absorption profiles of different species as a function of outflow velocity with respect to the QSO ($z_{\text{em}} = 0.629$). The Ne viii absorption is detected in seven components spread over a $\sim 2500$ km s$^{-1}$ velocity interval. The separate components are labelled in the figure. Apart from the two weak Ne viii components (1 and 7), all other components show O vi absorption with profiles very similar to that of Ne viii. The high-ionization Mg x, Al xii and O vi 5299 Å lines are clearly detected in the FUSE data but without blending only in components 3 and 5. Due to poor spectral S/N, the presence of stronger Mg x, Al xii and O vi 5299 Å lines can be confirmed only for component 3. Contamination from Galactic H2 lines has made the detection of Mg x and O vi ambiguous in all other components. At the velocities of components 3 and 4, we also find weak absorption consistent with N iii 989 Å and N iv 765 Å. The stronger N iii 6185 Å line ($f_\lambda \sim 1.7$ times) is a non-detection in the FUSE spectrum, and therefore we report the N(N iii) measurements for these components as upper limits. Very weak Lyβ and Lyγ absorption are seen in the COS data for component 3. But we do not find any Lyα absorption in the low-dispersion COS G230L spectrum in any of these Ne viii components.

The apparent column density profiles of Ne viii and O vii doublets, shown in Fig. 3, clearly indicate that the absorber is only partially

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Highly ionized outflow

Figure 2. Absorption profiles of different species for the associated absorber shown with respect to the ejection velocity from the QSO. The Lyα is from low-dispersion COS (G230L) spectrum whereas Mg x and O v are from FUSE. There are seven Ne vii components identified by the vertical dotted lines. The best-fitting Voigt profiles after correcting for partial coverage are overplotted as smooth red curves. Absorption lines unrelated to this system are marked by the shaded regions. The blue smooth curve in the Mg x panel are the synthetic profiles with column densities as predicted from the photoionization model (see text). The vertical solid lines in the Mg x and O v panels show the positions of Galactic H2 lines.

Figure 3. Panels (a) and (b): apparent column density profiles of the Ne vii and O vi doublets, respectively. The stronger and weaker transitions of the doublets are shown in red and blue, respectively. Panel (c): distributions of f_c for O vi (in red) and Ne vii (in blue). Panel (d): N(Ne vii)/N(O vi) measured in individual components labelled by the numbers. The mean and 1σ scatter of the ratio are shown in horizontal dotted lines. The contamination is shown by the shaded regions.

covering the background emitting source. The estimated covering fractions (f_c) using the method described in Srianand & Shankaranarayanan (1999) are also shown in Fig. 3. The covering fraction estimated for the Ne viii in components 2–7 is ∼0.6. The O vi absorption shows f_c ∼ 0.5 in components 2 and 3 and f_c ∼ 0.6 in components 4–6. The weak Ne viii absorption in component 1 is consistent with a complete coverage of the background source. It is interesting to note that the Ne viii and O vi ions have very similar covering fractions for all the components. This together with similar profile shapes suggests that the two ions are possibly tracing the same phase of the absorbing gas. The covering fraction of f_c ∼ 0.1 for H I determined using Lyβ and Lyγ of component 3 is significantly smaller, implying the kinematic coincidence of multiple gas phases with a different projected area (see also Telfer et al. 1998). The results of the Voigt profile fitting analysis after taking into account these effects of partial coverage are given in Table 1. In case of non-detections we calculate 3σ upper limits on the column densities using the rms error in the unabsorbed continuum at the expected position and by using the b value as measured for Ne viii (or O vi) with the appropriate f_c.

The most intriguing fact about this system is that in the five components where we have measurements of N(Ne viii) and N(O vi), we find a surprisingly constant value of 0.46 ± 0.16 for the log N(Ne viii)/N(O vi) ratio (see panel d of Fig. 3). To understand the physical conditions of the absorbing gas, we ran several photoionization models with CLOUDY v(07.02) (Ferland et al. 1998). In these models we assumed (a) the ionizing spectrum to be a combination of blackbody (with T ∼ 1.5 × 10^5 K) and power law with α_x = −0.7, α_y = −0.5 and α_ox = −1.6, as observed for HE 0238−1904 (see Fig. 1); (b) the gas is an optically thin plane-parallel slab; and (c) the relative abundances of heavy elements are similar to the solar values (Asplund et al. 2009).

In Fig. 4 various model-predicted column density ratios are plotted against ionization parameter. In the case of components 3 and 5, the observed N(Ne viii)/N(O vi), N(Mg x)/N(O vi) and N(Mg x)/N(Ne viii), within their 10 per cent uncertainty, are well...
reproduced for $\log U \sim 1.0$ and $1.1$, respectively. However, ratios involving low ions (i.e. O\textsc{iv}, N\textsc{iv} and O\textsc{vi}) require lower values of $\log U$, indicating the presence of multiple gas phases. By using $f_c = 0.6$, the covering fraction determined for Ne\textsc{viii}, we obtain an upper limit of $\log N$(H\textsc{i}) = 14.36 for the H\textsc{i} column density associated with the high-ionization gas. This gives a lower limit on metallicity of $log (Z/Z_\odot) \gtrsim -0.8$ for component 3. For all the components, the observed range of the $N$(Ne\textsc{viii})/$N$(O\textsc{vi}) ratio is consistent with $0.95 \leq \log U \leq 1.30$. Because of poor S/N of the \textsc{fus} data and the Galactic H\textsc{2} contamination, we could only check the consistency of Mg\textsc{x} profiles predicted by the models for other components. For each component we calculate the model predicted contaminations, we could only check the consistency of Mg\textsc{x} profiles predicted by the models for other components. For each component we calculate the model predicted $N$(Mg\textsc{x}) for $\log U$ required to produce the observed $N$(Ne\textsc{viii})/$N$(O\textsc{vi}). The profiles are then generated assuming $b$ and $f_c$ as those measured for Ne\textsc{viii}. The predicted Mg\textsc{x} profile is consistent with the observed spectra within measurement uncertainties (see Fig. 2), suggesting a similar value of $\log U$ for all these components spread over $\sim1800 \text{ km s}^{-1}$. Nitrogen is reported to be overabundant compared to oxygen in associated absorbers, favouring a rapid enrichment scenario in the central regions of QSOs (Hamann & Ferland 1992; Korista et al. 1996; Petitjean & Srianand 1999). The best-fitting photoionization model predicts $\log N$(N\textsc{v}) $\sim 13.5$. Even in a low-dispersion spectrum such a line should be detectable at the $\sim$4$\sigma$ level. The fact that we do not detect the N\textsc{v} line could be because (a) N is not overabundant compared to O and/or (b) the covering fraction of N\textsc{v} may be much less as it falls on top of Ly$\alpha$+N\textsc{v} emission lines. High-resolution data are needed to confirm the above-mentioned possibilities.

4 SUMMARY AND CONCLUSIONS

We report the detection of highly ionized outflowing gas through associated absorption from O\textsc{vi}, Ne\textsc{viii} and Mg\textsc{x} in the UV spectra of HE 0238$-$1904, which is presumably a non-BALQSO. The high S/N COS spectrum has allowed us to determine the covering fraction ($f_c$) and the multiphase physical conditions in the absorber. The similarity in the absorption profiles and $f_c$ suggests that O\textsc{vi} and Ne\textsc{viii} absorption possibly traces the same phase of the absorbing gas. Near constancy of $f_c$ for Ne\textsc{viii} and O\textsc{vi} in the different components spread over $\sim1800 \text{ km s}^{-1}$ indicates that the flow could be collimated.

Under photoionization equilibrium conditions, the log $N$(Ne\textsc{viii})/$N$(O\textsc{vi}) = 0.46 $\pm$ 0.16 ratio in the different components is consistent with $0.95 \leq \log U \leq 1.30$. This means that in spite of the absorbing gas being distributed over $\sim1800 \text{ km s}^{-1}$, the product $n_H r_e^2$ (where $r_e$ is the distance of the gas from the QSO) is

**Table 1.** Partial coverage corrected Voigt profile fit parameters.

| Species | $v_{\text{rest}}$ (km s$^{-1}$) | ID | $b$ (km s$^{-1}$) | $\log N$(cm$^{-2}$) | $f_c$ |
|---------|-------------------------------|---|-----------------|------------------|------|
| Ne\textsc{viii} | $-5767 \pm 9$ | (1) | 143.8 $\pm$ 12.7 | 14.22 $\pm$ 0.03 | 1.0 |
| H\textsc{i} | | | 143.8 | 13.71 | 1.0 |
| O\textsc{vi} | $-4743 \pm 20$ | (2) | 127.1 $\pm$ 20.2 | 14.67 $\pm$ 0.09 | 0.5 |
| Ne\textsc{viii} | | | 127.1 $\pm$ 0.0 | 15.14 $\pm$ 0.02 | 0.6 |
| H\textsc{i} | | | 127.1 | 13.70 | 1.0 |
| O\textsc{vi} | $-4539 \pm 6$ | (3) | 98.4 $\pm$ 5.7 | 15.11 $\pm$ 0.03 | 0.5 |
| Ne\textsc{viii} | | | 96.7 $\pm$ 1.9 | 15.45 $\pm$ 0.01 | 0.6 |
| O\textsc{iv} | | | 98.4 | 13.84 | 1.0 |
| O\textsc{v} | | | 98.4 | 14.45 | 0.5 |
| N\textsc{iii} | | | 98.4 | 13.29 | 0.5 |
| N\textsc{iv} | | | 98.4 | 13.61 $\pm$ 0.04 | 0.5 |
| Mg\textsc{x} | | | 98.4 | 15.32 | 0.6 |
| H\textsc{i} | | | 98.4 | 14.36(15.75) | 0.6(0.1) |
| Ne\textsc{viii} | $-3678 \pm 4$ | (4) | 94.9 $\pm$ 3.5 | 15.10 $\pm$ 0.02 | 0.6 |
| O\textsc{vi} | | | 96.8 $\pm$ 3.9 | 14.84 $\pm$ 0.02 | 0.6 |
| O\textsc{iv} | | | 96.8 | 14.39 | 0.6 |
| N\textsc{iii} | | | 94.9 | 13.79 $\pm$ 0.13 | 0.6 |
| N\textsc{iv} | | | 94.9 | 13.55 $\pm$ 0.04 | 0.6 |
| H\textsc{i} | | | 94.9 | 14.11 | 1.0 |
| Ne\textsc{viii} | $-3491 \pm 2$ | (5) | 63.8 $\pm$ 2.9 | 15.11 $\pm$ 0.02 | 0.6 |
| O\textsc{vi} | | | 68.3 $\pm$ 5.4 | 14.55 $\pm$ 0.03 | 0.6 |
| O\textsc{v} | | | 68.3 | 14.03 | 0.6 |
| Mg\textsc{x} | | | 68.3 | 15.11 | 0.6 |
| H\textsc{i} | | | 63.8 | 14.02 | 0.6 |
| Ne\textsc{viii} | $-3354 \pm 4$ | (6) | 37.8 $\pm$ 4.5 | 14.70 $\pm$ 0.06 | 0.6 |
| O\textsc{vi} | | | 39.0 $\pm$ 5.7 | 14.05 $\pm$ 0.06 | 0.6 |
| H\textsc{i} | | | 37.8 | 13.91 | 1.0 |
| Ne\textsc{viii} | $-3285 \pm 15$ | (7) | 40.6 $\pm$ 13.9 | 14.13 $\pm$ 0.21 | 0.6 |
| H\textsc{i} | | | 40.6 | 13.94 | 1.0 |

Notes. $^a$Relative velocity with respect to $v_{\text{em.}}$. $^b$Component ID as in Fig. 2. $^c$Covering fraction used for the fit. Rest-frame wavelengths and oscillator strengths are taken from Verner, Bartheb & Tytler (1994).
nearly a constant. Getting such a constraint naturally for different components could be an issue for the photoionization model. Models of mass-conserving shells expanding with a velocity $v$, predict $n_U r_c^2 v_c$ to be a constant. However, this is not the case in the present system as we do not find any clear trend between the ejection velocity and the ionization parameter. Alternatively, collisional ionization in gas with temperatures in the range of $5.7 \lesssim \log T (K) \lesssim 6.1$ can recover the observed $N(\text{Ne VIII})/N(\text{O VI})$ ratio as shown in the bottom panel of Fig 4. In this case, we expect $N(\text{Mg x})/N(\text{Ne VIII})$ or $N(\text{Mg x})/N(\text{O VI})$ to be very different between the different components, which cannot be ruled out with the existing FUSE data on $\text{Mg x}$. We note here that even in the case of photoionization, the equilibrium gas temperature is $\sim 1.2 \times 10^7 \ K$ for $\log U \sim 1.0$.

From the observed flux at the Lyman limit ($1.4 \times 10^{-14} \ \text{erg cm}^{-2} \ \text{s}^{-1} \ \text{Å}^{-1}$) in the QSO rest frame, we get a relation log $(n_U r^2_c) = 45.8 - \log U$. This gives log $(n_U r^2_c) = 44.8$ for $\log U = 1.0$. If we assume that the absorbing gas is well within the BLR ($r_c \lesssim R_{\text{BLR}}$), we get $n_U > 5 \times 10^8 \ \text{cm}^{-3}$. The cloud thickness along the line of sight is $\Delta r_\text{cl} \leq 2 \times 10^8 \ \text{cm}$, if we use $N(\text{H I}) \sim 10^{12} \ \text{cm}^{-2}$ and neutral fraction of $f_{\text{HI}} \sim 10^{-2}$ as found for the photoionization model at $\log U = 1.0$. The fact that the cloud is covering $\sim 60$ percent of the background emitting source gives the transverse size of the cloud as $r_\text{cl} \sim D_{2000} \sqrt{\tau_2} / 2 = 1.2 \times 10^7 \ \text{cm}$. This is $\sim 5$ orders of magnitude larger than the thickness along the line of sight (i.e. $\Delta r_\text{cl}/r_\text{cl} \sim 10^{-5}$), resembling a sheet-like geometry.

If we assume spherical geometry for the absorbing gas then the observed $f_c$ suggests that the radius of the cloud is $\sim 1.2 \times 10^7 \ \text{cm}$. This gives $n_U \sim 10^7 \ \text{cm}^{-3}$ and $r_c \sim 90 \ \text{pc}$ for $\log U = 1.0$. Therefore, the absorbing region, if nearly spherical, will be co-spatial with the absorbing region, if nearly spherical, will be co-spatial with the absorption region if $\log U = 1.0$. If we use $Z_{\text{HI}} \sim 0.2 Z_{\odot}$ without clear evidence for an enhanced N abundance. However, high-resolution spectra covering C IV and N V are needed to perform a detailed abundance analysis. High densities ($n_H$) inferred for the system suggest that HE 0238 $-$ 1904 is an ideal target for absorption-line variability studies. However, we do not find any signature of strong variation in the Ne VIII and O VI equivalent width from 2002 onwards from the HST/STIS and COS spectra. As this source is X-ray bright, the detection of warm absorbers will allow us to get further insight into this hot outflowing gas.

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