Galaxy Evolution and Feedback across Different Environments
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Outflows & Feedback from Extremely Red Quasars

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Abstract. Feedback from accreting supermassive black holes is often invoked in galaxy evolution models to inhibit star formation, truncate galaxy growth, and establish the observed black-hole/bulge mass correlation. We are studying outflows and feedback in a unique sample of extremely red quasars (ERQs) during the peak epoch of galaxy formation (at redshifts $2.0 < z < 3.4$). We identified ERQs in the Sloan Digital Sky Survey III (SDSS-III) Baryon Oscillation Spectroscopic Survey (BOSS) quasar catalog based on their extremely red i–W3 colors, but we find that ERQs typically have a suite of other extreme properties including 1) a high incidence of blueshifted broad absorption lines, 2) broad emission lines with unusually large rest equivalent widths (REWs), peculiar "wingless" profiles, and frequent large blueshifts (reaching $\sim$8740 km s^{-1}), and 3) characteristically very broad and blueshifted [OIII] 4959,5007Å lines that trace ionized outflows at speeds up to $\sim$6700 km s^{-1}. We propose that these ERQs represent a young quasar population with powerful outflows on the precipice of causing important disruptive feedback effects in their host galaxies.

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

1. Introduction

Luminous quasars have powerful outflows that might regulate star formation and mass assembly in their host galaxies (Weinberger *et al.* 2017; Hamann *et al.* 2019). Evolution models predict that early SMBH growth and accompanying quasar/AGN activity occurs mostly in obscurity, deep inside dusty starburst host galaxies. Outflows driven by star formation and the central quasar/AGN activity then combine with consumption of the gas and dust to quench star formation and reveal visibly luminous quasars in galactic nuclei (Sanders *et al.* 1988; Veilluex *et al.* 2009).

Quasars that are obscured and reddened by dust can provide important tests of this galaxy/quasar evolution picture because they are expected to appear preferentially during the brief transition/blowout phase when quasars are still partially embedded in a dusty starburst and, perhaps, the effects of quasar-driven feedback to the host galaxies are most prominent (Glikman *et al.* 2015; Assef *et al.* 2015; Banerji *et al.* 2015). It is helpful to exclude Type 2 quasars from this discussion because they are generally expected to be normal quasars with obscuration caused by orientation effects (Netzer 2015). In contrast,

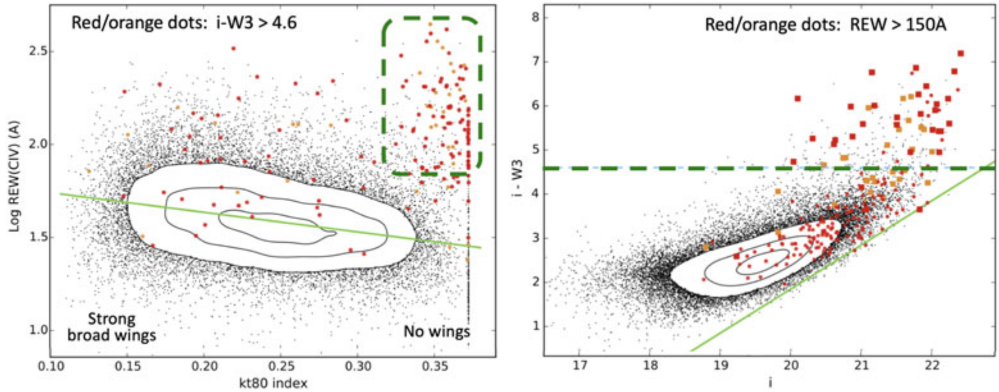

Figure 1. *Left panel:* Log REW(CIV) versus the CIV profile kurtosis, kt80, for BOSS quasars at redshifts $2.0 < z < 3.4$. The red and orange symbols mark Type 1 and 2 ERQs, respectively defined by i–W3 > 4.6. They are strongly clustered to the upper right, e.g., with large REWs and wingless line profiles. *Right panel:* i–W3 color versus i magnitude for these same BOSS quasars. The solid green line shows approximate sensitivity limit of WISE in the W3 filter. The red and orange dots again indicate Type 1 and 2 quasars, respectively, here with REW(C IV) > 150 Å. The red and orange squares additionally indicate "wingless" profiles with kt80 > 0.33. The dashed green line marks the ERQ threshold at i–W3 > 4.6. See Hamann *et al.* (2017).

red Type 1 quasars provide direct views of quasars whose enhanced obscuration might be connected to a young dusty stage of host galaxy evolution.

2. Extremely Red Quasars (ERQs)

Our team discovered a unique new population of extremely red quasars (ERQs) at redshifts $z \sim 2.0$–3.4 in the SDSS-III BOSS and WISE mid-IR surveys (Ross *et al.* 2015; Hamann *et al.* 2017). We identify ERQs based on extremely red colors in i–W3 > 4.6 (AB), as shown in the right panel of Figure 1. The i and W3 filters sample rest-frame $\sim 0.2\mu$m and $\sim 3.4\ \mu$m, respectively, at the median redshift of our sample. Our ability to find even redder quasars is limited by the i $\lesssim 22$ limit of the BOSS survey. ERQs selected this way have large bolometric luminosities, $L \gtrsim 10^{47}$ ergs/s, normal radio emission (roughly 8% radio loud), and sky densities that are a few percent of similarly-luminous blue (unobscured) quasars (Hamann *et al.* 2017). These basic characteristics are similar to other red quasar samples such as hot dust-obscured galaxies (HotDOGs, Assef *et al.* 2015; Tsai *et al.* 2015) and highly-reddened Type 1 quasars (Banerji *et al.* 2013, 2015), and they are consistent with ERQs representing a brief obscured phase of quasar activity.

However, many ERQs have a suite of other extreme properties unlike any known quasar population. Most obvious in the BOSS spectra are UV broad emission lines with 1) very large rest equivalent widths (REWs), 2) unusual "wingless" profiles, and 3) peculiar line strength ratios. Figure 1 shows, specifically, how ERQs with i–W3 > 4.6 have a strong preference for large REWs and wingless profiles (large kurtosis, kt80) in the CIV 1549Å broad emission line. Roughly 50% of the reddest ERQs, with i–W3 > 5.6, have REW(CIV) > 150 Å compared to only 0.4% of similarly-luminous blue quasars (Hamann *et al.* 2017). The left panels in Figure 2 show examples of this behavior in two ERQs. Notice, in particular, the dramatically stronger broad emission lines and unusual line profiles in the ERQs compared the median SDSS quasar (from vanden Berk *et al.* 2001). Also notice the unusually weak broad Lyα emission lines and the great strength of NV 1240Å relative to CIV 1549Å.

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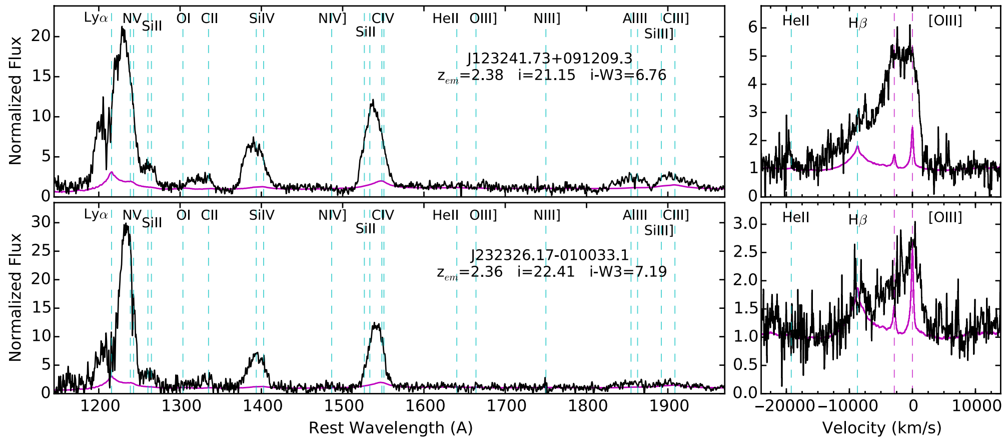

Figure 2. Normalized spectra of two ERQs in the rest UV (left panels) and across the [OIII] 4959,5007A and Hβ lines in the visible (right). The magenta curves show the composite spectrum of normal blue quasars in SDSS (vanden Berk *et al.* 2001). Compared to this normal quasar spectrum, ERQs have very strong and blueshifted NV and CIV broad emission lines, peculiar line profiles, and spectacularly broad and blueshifted [OIII] lines at speeds reaching >6000 km s^{-1}. The [OIII] lines identify powerful outflows that could be driving important feedback effects in the host galaxies (Zakamska *et al.* 2016; Hamann *et al.* 2017; Perrotta *et al.* 2019.

Another common property of ERQs is large blueshifts in CIV 1549Å and other broad emission lines. These blueshifts identify outflows in quasar broad emission-line regions (BELRs, Richards *et al.* 2011). The two ERQs shown in Figure 2 have CIV blueshifts >2500 km s^{-1} relative to a rest frame (blue dashed vertical lines) defined by the low-ionization emission lines of SiII and MgII (not shown). Figure 3 shows more examples of large CIV blueshifts measured relative to narrow emission-line spikes in Lyα, that appear (from Keck KCWI imaging spectroscopy) to be part of extended Lyα emission halos. These results provide additional confirmation of large CIV blueshifts in ERQs, including the largest blueshift ever reported in a quasar spectrum at v$\approx$8740 km s^{-1} (bottom panel in Fig. 3). Overall, we estimate that CIV blueshifts >2500 km s^{-1} are roughly 50 times more common in ERQs than normal blue quasars at the same redshifts and luminosities (Hamann *et al.* 2017).

We also find that ERQs have a high incidence of blueshifted broad *absorption* lines (BALs) and other BAL-like features in their spectra. We estimate that the incidence of these outflow absorption lines is roughly 3 times greater in ERQs compared to the normal blue quasar population (Hamann *et al.* 2017).

Perhaps the most remarkable property of ERQs is their strong tendency to have broader and more blueshifted [OIII] 4959,5007Å emission lines than blue quasar samples. This includes the broadest and most blueshifted [OIII] lines ever reported in quasars, with FWHMs and blueshifted wings reaching ~6700 km s^{-1} (Zakamska *et al.* 2016; Perrotta *et al.* 2019). The right-hand panels in Figure 2 show examples of this extreme [OIII] behavior compared to the median spectrum of SDSS quasars. The left panel in Figure 4 shows more generally how the large [OIII] outflow speeds (e.g., v_{98} measured from the [OIII] line wings) are strongly correlated with red i–W3 colors, e.g., much more so than a previously-known weaker relationship to quasar luminosities. The right panel in Figure 4 shows further that, with reasonable standard assumptions about the outflow densities and sizes, the [OIII] outflows in ERQs have kinetic powers at least several times larger than similarly-luminous blue quasars. Importantly, the derived [OIII] outflow kinetic luminosities, roughly in the range 1–10% of the quasar bolometric luminosities,

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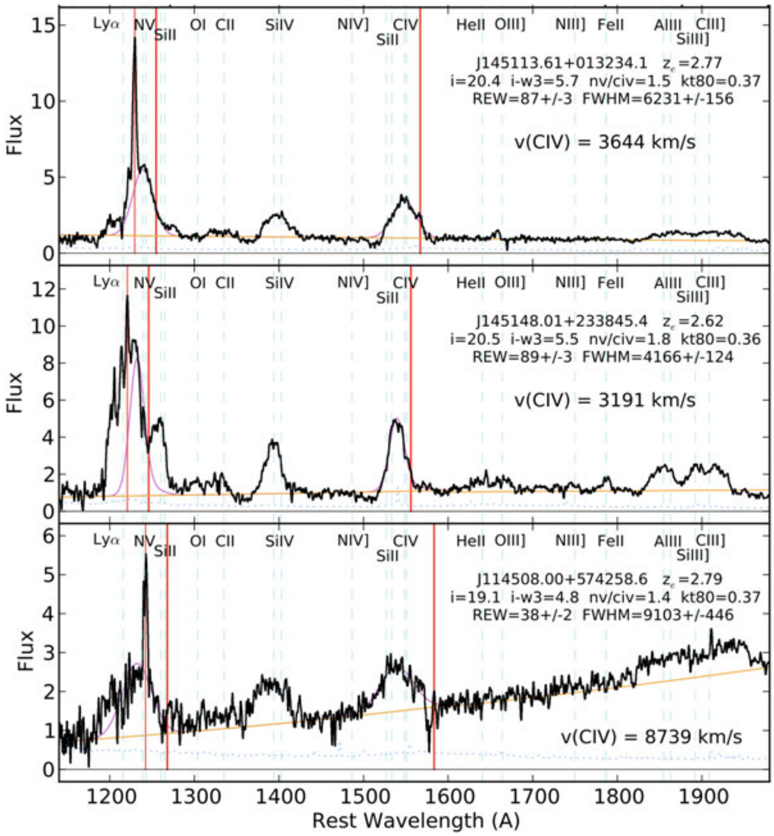

Figure 3. Rest UV spectra of several ERQ with large CIV blueshifts measured relative to narrow Lyα emission-line "spikes" (FWHM$<$1000 km s^{-1}) that form in spatially extended regions around the quasars in the host galaxies and circumgalactic halos. The vertical red lines mark the expected wavelengths of Lyα, NV, and CIV in the this halo frame. The CIV blueshifts relative to this frame, indicated by v(CIV), including the largest emission-line blueshift ever reported at 8739 km s^{-1} (bottom panel). Other emission-line data for CIV are included in the upper right of each panel. These large emission-line blueshifts combined with a high incidence of blueshifted BALs and consistently large [OIII] outflow speeds indicate that ERQs have unusually powerful outflows across spatial scales from $\lesssim$1 pc to $\gtrsim$0.5 kpc.

are larger than recent estimates of the minimum needed for important feedback to the host galaxies (Hopkins & Elvis 2010, see Perrotta *et al.* 2019).

3. Implications

The exotic spectral properties of ERQs might be manifestations of exceptionally powerful accretion-disk outflows, perhaps during an early dusty stage of galaxy/quasar evolution. The higher incidence of BALs and BAL-like outflow lines is consistent with enhanced outflow activity, although orientation effects cannot be ruled out for these absorption-line features. The broad emission lines with unusually large REWs, wingless profiles, and frequent large blueshifts are similarly consistent with enhanced outflow activity in the BELRs (Hamann *et al.* 2017). In particular, the large blueshifts are direct outflow signatures, while the large REWs and wingless profiles might result from unusually extended BELR outflows that intercept and reprocess more of the continuum flux into line radiation (leading to large REWs) with narrower profiles that emphasize the

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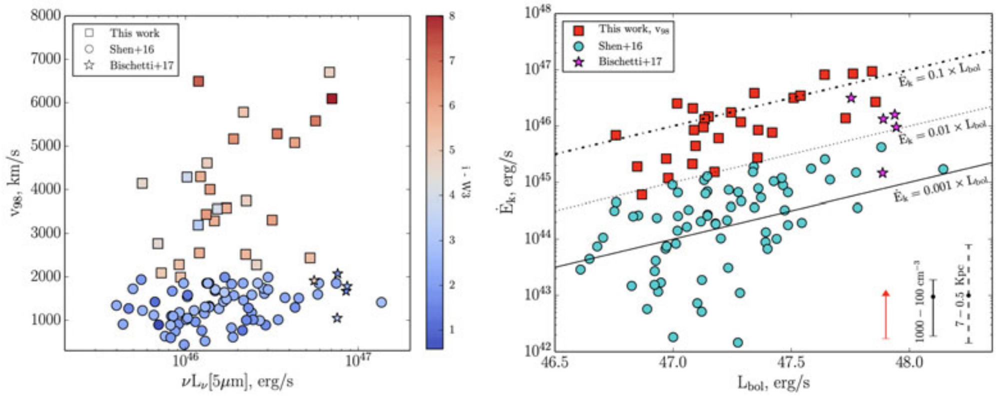

Figure 4. *Left panel:* [OIII] outflow speed (v_{98}) versus mid-IR luminosity for ERQs (squares), and luminous blue quasar samples from Shen (2016, $z \sim 1.5{-}3.5$) and Bischetti *et al.* (2017, $z \sim 2.3{-}3.5$). The symbol colors indicate their i–W3 color according to the blue–red color to the right. *Right panel:* Kinetic power in the [OIII] outflows versus quasar bolometric luminosities. The black error bars in the lower right indicate the range of values that would result for different assumed densities and radial outflow sizes. The calculations use *observed* [OIII] fluxes. The red arrow in the lower right shows the typical extinction correction that should be applied to the ERQs. For reasonable assumptions, the ERQ outflows have kinetic power in the range ∼1% to ∼10% of their bolometric luminosities, which is easily sufficient for feedback in theoretical models (Hopkins & Elvis 2010). From Perrotta *et al.* (2019).

outflow component rather than the broad wings that are generally attributed to emission regions close to the accretion disks. The uniquely broad and blueshifted [OIII] lines in ERQs are perhaps the most direct indicators of unusually powerful outflows. These lines require relatively low densities and therefore extended emitting regions $\gtrsim$0.5 kpc from the central quasars, where they might directly cause feedback to the host galaxies (Zakamska *et al.* 2016; Perrotta *et al.* 2019). However, a tentative result from our ongoing IFU observations with Keck OSIRIS is that the [OIII] outflows in ERQs are compact on scales $\lesssim$1.5 kpc. This is consistent with ERQs being young objects, where the outflows have not had time to expand into the host galaxies. It might also explain the unusually high [OIII] outflow speeds if this gas has not yet impacted and swept up substantial material in the host galaxies. Our working hypothesis is that ERQs are indeed young objects with powerful outflows whose feedback effects have not yet reached their extended host galaxies.

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