Searching for the signature of radiative line driving: On the absence of Ly α–N v line-locking features in a large sample of BALQSOs

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ABSTRACT

We have searched the hybrid BALQSO catalogue of Scaringi et al. derived from data release 5 of the Sloan Digital Sky Survey in order to compile the largest sample of objects displaying spectral signatures which may be indicative of radiative line driving. The feature in question is the “ghost of Ly-α”, a line-locking feature previously identified in the broad C iv and Si iv absorption lines of a small fraction of BALQSOs, and formed via the interaction of Ly-α photons with N v ions.

We test, where possible the criteria required to produce an observable ghost feature. These criteria include: significant broad absorption, strong intrinsic Ly-α emission, narrow Ly-α, strong N v absorption, and a weak far-UV continuum. No single ghost-candidate meets all of these criteria. Furthermore, we find that these criteria are not met significantly more often in ghost-candidates than in a comparison sample chosen to exhibit relatively featureless broad absorption troughs. Indeed, the only significant differences we find between our ghost-candidate and comparison samples, is that on average, our ghost-candidate sample displays (i) significantly stronger N v absorption, and (ii) the onset of absorption occurs at lower velocities in our ghost-candidate objects.

Significantly, we find no evidence for an excess of objects whose absorption troughs bracket the location of the Ly-α–N v line-locking region, rather the location of ghost-like features appears to be independent of any systematic velocity, with comparable numbers appearing both redward and blueward of the ghost-zone. Thus, the majority of objects identified here as strong ghost-candidates are likely multi-trough interlopers whose absorption feature simply bracket the region of interest.

Key words: galaxies:active, quasars:absorption lines, quasars:general

1 INTRODUCTION

Broad absorption line quasars (BALQSOs) as their name suggests, show strong broad blue-shifted absorption lines in their spectra believed to be indicative of high velocity (~0.1c) out-flowing winds. BALQSOs represent approximately 15% of quasars in general (Reichard et al. 2003a; Trump et al. 2006; Knigge et al. 2008; Scaringi et al. 2009). The majority (~ 85%) (Sprayberry and Foltz 1992; Reichard et al. 2003b) of BALQSOs are known as HiBALs, displaying absorption in lines of high ionisation only (e.g. N v, Si iv, and C iv). The remainder are classified as LoBALs and show in addition broad absorption in lines of low ionisation species, most notably Al iii and Mg ii. LoBALs are further sub-classified according to the presence of Fe absorption, the Fe LoBals. Since the spectra of LoBals are in general redder than HiBals, Becker et al. (2000) suggests that BALQSOs and in particular Fe LoBALs may be an early phase in the development of emerging or re-fuelled quasars.

There has been much debate about the relationship between BALQSOs and the general quasar population as a whole. Simple unification schemes, suggest that BALQSOs and non-BALQSOs are similar objects and that any observed differences in their spectra arise due to orientation effects (Ogle et al. 1999; Weymann et al. 1991; Schmidt and Hines 1999; Elvis 2000). In this picture, the relative fraction of BALQSOs to non-BALQSOs has a sim-

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ple geometric interpretation, representing the fraction of sky, as seen from the source, obscured by gas (ie. the source covering fraction), which in the simplest case, can be related to the flow geometry (e.g. opening angle).

In recent years interest in BALQSOs outflows has risen sharply, principally because of the realisation that such high velocity outflows carry a substantial amount of energy and momentum into the ISM, and may therefore be important in driving AGN feedback as well as providing a mechanism for quenching star formation (Scannapieco, Silk and Bouwens 2004). Indeed, the discovery of highly ionised, very high-velocity X-ray outflows (e.g. Pounds et al. 2003a, 2003b; Pounds and Reeves 2009), for which the energy transport (in terms of mechanical energy) is large enough to interrupt the growth of the host galaxy, may provide the causal link behind the well-known correlation between the mass of the central black hole and the mass of the bulge (e.g. Ferrarese and Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002).

However, despite the increasing importance of these outflows the precise mechanism responsible for accelerating them to high velocity remains uncertain, with radiative acceleration (Shlosman et al. 1983; Arav and Li 1994; Murray et al. 1995; Proga et al. 2001; Chelouche and Netzer 2001), Magneto Hydro Dynamic (MHD) driven winds (Blandford and Payne 1982; Emmering et al. 1992; Konigl and Karttunen 1994; Bottorff et al. 1997) and thermally driven winds seen as the main contenders (see e.g. Proga (2007) for a review). A major hindrance to progress in this area is the absence of a clean discriminatory observational signature of what are essentially orthogonal wind geometries. For radio-quiet objects, AGN unification schemes tend to favour equatorial wind geometries (e.g. Elvis 2000). By contrast, observations of radio-loud BALQSOs (Becker et al. 1997; Brotherton et al. 1993) and in particular polarisation observations of PKS 0400-005 indicate a non-equatorial BAL outflow (Brotherton et al. 2006). One possible explanation for the apparent difference in wind geometry between radio-loud and radio-quiet objects, is that different acceleration mechanisms operate in these two classes of objects.

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The aim of this paper is twofold: (i) to compile the largest sample of uniformly selected ghost-candidate spectra, and (ii) attempt to determine the origin of their ghost features, by testing on a source by source basis, whether they meet the original criteria as set out by Arav (1995) necessary for ghost-features to be observed. In §2 we describe the mechanism proposed for ghost formation and outline Arav’s criteria for the production of strong ghost signatures. Selection of those objects comprising our ghost-candidate spectra and our non-ghost control sample is described in §3. In §4 we present the results of testing each of the spectra in our ghost-candidate and comparison samples against each of the criteria in turn necessary for the formation of an observable ghost feature. We discuss the implications of our findings in §5. Our conclusions are summarised in §6.

2 THE GHOST OF LY-α

The feature that is poetically known as the ghost of Ly-α is a hump seen in the absorption trough of a small fraction (less than 5%, Arav 1995, North et al. 2006) of BALQSOs located 5900 km s\(^{-1}\) blue-ward of the centre of the line to which the absorption is attributed. The feature was first investigated by Korista et al. (1993) after being seen in a difference spectrum of BALQSO and non-BALQSO spectral composites produced by Weymann et al. (1991) who pointed out that the difference between the two absorption troughs was approximately equal to the velocity separation of N\(^v\) and Ly-α. In a series of papers in the mid 90’s Arav and Li 1994; Arav, Li and Begelman 1994 Arav and Begelman 1994; Arav et al. 1995; Arav 1996 Arav suggested that the feature seen at this velocity was a result of the increased radiative pressure on N\(^v\) ions at this velocity within the outflow. In this picture N\(^v\) ions moving at 5900 km s\(^{-1}\) ‘see’ the Ly-α emission from the AGN at the energy of their own emission resulting in a large increase in the scattering cross section of the Ly-α photons. Consequently, out-flowing N\(^v\) ions receive an increase in radiation pressure leading to a large injection of momentum into the outflow. The out-flowing ions of other species are dragged to higher velocities by electromagnetic interactions with the N\(^v\) ions, leading to a deficit of material at this velocity (because each out-flowing ion spends very little time at this velocity before being accelerated to greater velocities). In turn this causes a decrease in the opacity at this velocity which manifests as a peak within the absorption troughs of the out-flowing species.

This simple mechanism explains both the presence of the feature and why it’s position is linked to the rest frame of the source. Arav (1996) suggested that the reason for the feature being most prominent in C iv absorption rather than in other species, is that the doublet separation of C iv is far smaller (498 km s\(^{-1}\)). By comparison the larger doublet separations of Si iv (1933 km s\(^{-1}\)) and O vi (1647 km s\(^{-1}\))
result in the feature being blurred over several thousand km s\(^{-1}\), producing a low contrast feature which is difficult to detect in low S/N data. For this reason, in this study we confine our search for ghost features to the \(\text{C}\ IV\) broad absorption line only.

Since Ly-\(\alpha\) and N \(\text{v}\) are amongst the strongest UV lines in AGN spectra, an obvious question to ask is why aren’t ghost-features ubiquitous amongst the general BALQSO population? To answer this, Arav proposed a set of physically motivated criteria which had to be met before ghost features would be observable. These are:

(i) Significant broad absorption in the region between 3000 and 9000 km s\(^{-1}\) blue-ward of line centre,
(ii) Strong intrinsic Ly-\(\alpha\) emission,
(iii) Narrow Ly-\(\alpha\) emission,
(iv) Strong broad N \(\text{v}\) absorption,
(v) Little far-UV flux between between \(\lambda\)200\(\text{\AA}\) and \(\lambda\)1000\(\text{\AA}\).

The first criterion is simply a statement that ghost-features can only be observed if significant photon scattering is occurring. The second criterion implies that there must be a significant flux of Ly-\(\alpha\) photons, while the third requires that the line-emitting gas has a relatively narrow spread in velocities so that the resulting feature is not spread over a large range of velocity reducing the contrast. Since the dominant scattering ion is N \(\text{v}\), strong N \(\text{v}\) absorption is also needed. The final requirement, and the most difficult to measure, recognises that in order for Ly-\(\alpha\)–N \(\text{v}\) line-locking to dominate the dynamics of the flow, there cannot be significant far-UV line driving (Korista et al. 1993).

3 SELECTION OF GHOST-CANDIDATE SPECTRA

BALQSOs represent \(~15\%\) of the quasar population (see e.g. Knigge et al. 2008 and references therein), of these, between \(~20-25\%\) show evidence for multiple troughs [Korista et al. 1993 (North et. al 2006)]. Amongst the multi-trough objects, ghost candidates are likely rare representing less than a few per cent of BALQSOs (Arav 1995) because of the stringent requirements for ghost observability. Thus in order to find significant numbers of ghost-candidates, large quasar samples are required.

All previous ghost candidate samples have been limited to just a handful of objects (North et. al. 2006; Arav 1994). By comparison, Data Release 5 (DR5) of the Sloan Digital Sky Survey (SDSS) contains 77,429 quasars of which 28,421 have redshifts between 1.7 and 4.2 allowing C \(\text{IV}\) and any associated absorption to be seen in their optical spectra. We require a visible C \(\text{IV}\) BAL because although radiative line driving will produce a feature in all absorption troughs, the resultant hump will be most easily observed in the C \(\text{IV}\) absorption trough because of the small doublet separation of this line. Several BALQSO samples have been compiled from the various data releases of the SDSS (Reichard et. al 2003a; Trump et. al. 2006; Knigge et al. 2008) and from DR5 (Gibson et. al. 2008; Scaringi et. al. 2009). Here we adopt the BALQSO catalogue of Scaringi et. al. (2009), containing 3,552 BALQSOs. The Scaringi et al. sample, differs from other samples in that it does not rely on simple metrics such as the Balnicity index (Bl, Weymann et al. 1991) or Absorption index (AI, Hall et al. 2002, Trump et al. 2006) to identify and classify BALQSOs. Rather it uses a robust hybrid method, involving gross classification with a supervised neural network (learning vector quantisation) and the visual inspection of outliers.

To identify strong ghost candidates we have performed five cuts on this BALQSO sample. The first cut eliminates noisy spectra (S/N \(<4\) per pixel), estimated in two line-free continuum bands from \(\lambda\)1650–1700\(\text{\AA}\) and \(\lambda\)1700–1750\(\text{\AA}\). To reduce contamination from emission, absorption and cosmic rays that may be present in either bin we take the greater of the two values as our S/N estimate. The second cut removes all objects which show an apparently single smooth absorption trough. Following this cut we are left with only those objects which display multiple absorption trough features (1019 in total)\(^2\).

A third rejection cut removes those objects that contain 2 or more peaks within the absorption trough (numbering 761). These objects are eliminated to reduce contamination by objects which display absorption from multiple out-flowing regions which by chance happen to lie at velocities corresponding to the ghost-zone. This leaves just 258

\(^2\) Approximately 28\% (1019 out of 3552) of our BALQSOs show evidence for multiple troughs. This compares favourably with previous studies by North et. al. (2006) who found that 58 out of 224 (26\%) of BALQSOs from SDSS EDR showed evidence of multiple-troughs, and Korista et al. (1993) who found 16 out of 72 objects (22\%) showed multiple-troughs.
objects which contain a single-peak (or alternatively double-trough) within the C iv absorption region.

Figure 1 (upper panel) shows our multi-trough composite spectrum (solid line) created from taking the geometric mean of all objects rejected at this stage after normalising the flux between $\lambda\lambda 1700–1750\text{\textmu}m$ to unity. In order to highlight the absorption regions, we also plot a non-BALQSO composite spectrum (dashed line). The non-BALQSO composite is the geometric mean of all of the quasar spectra in the SDSS DR5 quasar catalogue in the redshift range $1.7 < z < 4.2$ excluding those objects which are also in the BALQSO catalogue of Scaringi et al., and reddened to fit to the continuum windows in the multi-trough composite spectrum using the SMC extinction law of Pei (1992). For completeness, the middle and lower panels show two example spectra rejected at this stage. Each object shows a clear peak located just outside of the limits of the ghost zone. Interestingly, this composite spectrum shows some evidence of a feature at the low velocity edge of the ghost zone. One possible explanation for this feature is that these objects are genuine ghost-candidates with poorly assigned redshifts. However, on closer inspection of the objects rejected at this stage we find no evidence for features outside of the ghost zone due to random redshift errors. Alternative explanations for the origin of this feature include, (i) intrinsically weaker absorption at lower velocities, or (ii) an abrupt change in the intensity of the (overlying) emission at these velocities.

We make one further cut to remove those objects which do not show significant broad absorption either side of the ghost feature extending from 3000 to 9000 km $s^{-1}$ blue-ward of the emission-line. This cut is chosen to eliminate objects with deep narrow absorption features whose alignment mimics the presence of a ghost feature. Figure 3 (upper panel, solid line) displays the composite spectrum of all objects rejected at this stage, while in the middle and lower panels, we give examples of individual objects rejected by this cut. Though the composite spectrum shows a clear feature within the ghost zone, it is not smooth, instead displaying sharp narrow features, whose separation is larger than the
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Figure 4. Top-Panel: Geometric mean composite spectrum of our ghost-candidate sample of 43 objects. Middle and lower panels: example spectra of individual objects making up this sample. The dashed vertical lines indicate the location of the ghost-zone.

doublet separation of C iv. This reflects both the narrowness of the absorption features (since intrinsically broad humps would be smoothed out in the averaging process yielding low contrast features) which make up this composite, and in addition small differences in their velocities relative to the rest-frame of the source. These differences may result from these features being unrelated to the ghost mechanism and appearing in the ghost zone by chance though we cannot preclude the fact that some of the objects rejected at this stage are indeed true ghost-candidates.

Our final sample of 43 ghost-candidate objects comprises the largest sample of objects exhibiting the ghost of Ly-α and the first to allow a statistical analysis of the properties of these objects. Figure 4 shows the geometric mean composite ghost-candidate spectrum (solid line), together with a non-BALQSO composite spectrum (dashed line), and two example ghost-candidate spectra (middle and lower panels). Our final ghost-candidate composite spectrum displays a clear smooth double-trough structure located firmly within the ghost zone of a relatively broad absorption trough. Visual comparison of this composite with that formed from objects rejected at the previous stage (i.e. those with insufficient absorption either side of the ghost-zone), indicates that our final sample displays on average narrower Ly-α and C iv emission-lines, stronger Ly-α emission and deeper N v absorption (fulfilling 3 of Arav’s criteria for forming observable ghost features), as well as broader Si iv absorption, and suggests that we are indeed isolating those objects most likely to form observable ghost features. Figure 4 summarises the various cuts made in the creation of our ghost-candidate sample.

Figure 5. Flow diagram showing the number of objects rejected at each step in our ghost selection algorithm.

3.1 Selecting a Comparison Sample

Of the 43 strong ghost-candidates, 21 are at large enough redshift $z > 2.15$ to place Ly-α above the atmospheric cut-off and thus allow us to test for each object all of the criteria deemed necessary for ghost-formation. These are listed in the upper half of Table 1. For the remainder, their redshifts are too low to allow a direct measurement of the strength and width of the Ly-α emission-line. For these objects we estimate the strength and width of the Ly-α emission-line using the C iv emission-line as a surrogate, and substantiated by known correlations between the two lines (see e.g. Wilkes 1984, Ulrich 1989). These objects are listed in the lower half of Table 1. For completeness, we have also compiled a sample of BALQSOs showing no evidence for a ghost feature or multiple trough. This allows us to compare the relative frequency with which the ghost-formation criteria are met amongst BALQSOs both with and without ghost features. In order to create such a sample we have performed a number of cuts on the Scaringi et al. (2009) BALQSO sample. As for our ghost-candidate sample we first select for $\text{S/N} > 4$, and then select those objects with $z > 2.15$ to allow inspection of the N v and Ly-α emission-lines necessary to test for the presence of strong narrow Ly-α emission and strong N v absorption. The remaining spectra are then visually inspected and any object showing multiple absorption troughs or any other hint of a ghost feature are removed.
from the sample. We also remove those objects which do not show significant absorption between 3000 and 9000 km s$^{-1}$. This leaves just 26 objects showing significant C$^{\text{iv}}$ absorption between 3000 and 9000 km s$^{-1}$ with no evidence for a ghost feature or multiple trough. One of these objects SDSS J101056.68+355833.3 shows evidence for a ghost feature in the Si$^{\text{iv}}$ absorption line (see A5) and is therefore also removed from our comparison sample leaving just 25 objects. A summary of the rejection cuts made in the creation of our comparison sample is given in Figure 6. The geometric mean composite spectrum of our comparison sample is indicated by the dotted line in Figure 7. Aside from substantially weaker N$^{\text{v}}$ absorption, the strengths and widths of the emission-lines in the comparison sample composite spectrum match those of the ghost candidate composite spectrum remarkably well. The main difference between these two composite spectra appears to be the absence of the low-velocity absorption trough in the comparison sample spectrum. We do not believe this difference arises from the way in which the two samples were selected. 

In §4 we use our ghost-candidate sample to test, where possible, the criteria set out by Arav (1996) required by radiative acceleration models to produce an observable ghost feature. We compare the relative frequency by which our ghost candidate spectra meet the criteria necessary for the formation of observable ghost features with our non-ghost comparison sample.

### 4 TESTING THE CRITERIA FOR THE FORMATION OF OBSERVABLE GHOST FEATURES

In this section we present the results of testing the criteria for the formation of observable ghost features. We first concentrate on the sample of 21 ghost-candidate objects for which all of the criteria may be tested and compare these results with those obtained using our non-ghost comparison sample. We then move on to our remaining objects and test where possible whether these objects satisfy the necessary criteria.

#### 4.1 Significant C$^{\text{iv}}$ broad absorption line

All of the objects in our ghost candidate sample will clearly show significant absorption in the region between 3000 and 9000 km s$^{-1}$ blue-ward of the C$^{\text{iv}}$ emission line as this is required in order to see any potential ghost feature. This criterion is required purely because in order to effect the out-flowing C$^{\text{iv}}$ ions in an observable way this outflow must reach significant optical depth and appear as a BAL trough within the spectrum. Our comparison sample has also been chosen to exhibit strong broad absorption, so naturally also fulfils this criterion.

#### 4.2 Strong Intrinsic Ly-$\alpha$ emission

In order for the effects of Ly-$\alpha$ radiation on N$^{\text{v}}$ to cause a significant increase in the radiation pressure on the outflow as a whole the Ly-$\alpha$ emission line must be intrinsically strong. However, since the ghost of Ly-$\alpha$ is produced by scattering Ly-$\alpha$ photons it can be extremely difficult to measure the strength of the intrinsic Ly-$\alpha$ emission-line. Hence Arav et al. (1995) modified this criterion to allow the C$^{\text{iv}}$ and N$^{\text{v}}$ emission-lines to be used in situations where the Ly-$\alpha$ emission-line was either significantly absorbed, or had insufficient spectral coverage. This modified criterion requires Ly-$\alpha$ emission to be at least 300% above the continuum and/or both C$^{\text{iv}}$ and N$^{\text{v}}$ to be at least 100% above the continuum. They note that ‘the latter criterion is hardly ideal but observations of non-BAL quasars show that the line strengths roughly scale together’ (Arav et al. 1995). Here we isolate the continuum emission using the specfit package in IRAF. We model the continuum as a reddened power law and fit to the continuum in regions free of contaminating emission- and absorption-lines, where possible. This can be particularly difficult for objects with the highest

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Figure 6. Flow diagram showing the number of objects rejected at each step in our comparison sample selection algorithm.

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3 We note that measuring the strength of a line according to its peak flux can be misleading, since it implies that the underlying line profiles are similar for all objects (and thus the total flux in the line simply scales with the peak flux). For example, a comparison between the C$^{\text{iv}}$ emission-line of the composite spectra in Figure 7 suggests that both our ghost-candidate and comparison samples display a narrower underlying C$^{\text{iv}}$ emission-line. If the widths of the other emission-lines scale with the C$^{\text{iv}}$ emission-line width, then we would expect both the Ly-$\alpha$ and N$^{\text{v}}$ emission-lines to be similarly narrow.
velocity out-flows as there are few emission/absorption line-free regions. Furthermore, we have not attempted to fit for the continuum short-ward of A1280Å as this region is typically so absorbed and the line-emission so highly blended that no clean continuum regions can be identified. Instead, we fix the continuum strength at short wavelengths to that measured between λλ1315–1350Å. This approach is chosen to avoid overestimating the strength of the broad absorption, at the expense of overestimating the strength of the line-emission in a few cases.

In objects whose spectra cover the Ly-α region, 86% (18/21) of the ghost candidate sample meet the criterion for strong emission-lines compared to 88% (22/25) of the comparison sample. Inspection of the composite spectra for the two samples (Figure 7), indicates that the strength of the Ly-α emission-line (relative to the continuum) is broadly similar in the two samples, and both are weaker relative to the non-BALQSO composite, due to the presence of strong N v and Ly-α absorption. For the other lines, the N v emission-line appears stronger on average in our ghost-candidate and comparison samples relative to non-BALQSOs, while there appears little difference in the strength of the C iv emission-line, though we note that in so far as we can measure them, their emission-line widths appear to be narrower on average.

4.3 Narrow emission-lines

Models of outflows accelerated by radiative line driving produced by Arav and Begelman (1994), Arav et al. (1993) suggest that once the line widths exceed 3500 km s$^{-1}$ (FWHM) potential ghost features become undetectable. This is because broader emission-lines will result in a broader, lower contrast feature (since the core of the line, where most of the scattering occurs, is weaker relative to the wings in a broad emission-line c.f a narrow emission-line) which is difficult to detect particularly in low S/N data. Unfortunately, determining the width of the underlying emission-lines in BALQSOs is extremely difficult as the broad absorption in these objects prevents accurate measurements of the shape and strength of the underlying emission-lines and continuum. Given how our ghost-candidate sample was selected we expect almost all of the ghost-candidates to show significant absorption in the blue wing of Ly-α, N v and C iv, while our comparison sample was chosen to exhibit strong relatively featureless absorption in the blue wing of C iv.

Since we cannot make an accurate measurement of the width of the emission-line we instead attempt to estimate its likely width using the C iv emission-line width as a surrogate. For the majority of sources, C iv is severely absorbed, so we estimate its underlying un-absorbed width using model fits to the red wing of the emission-line. We use the same underlying fit for the continuum as was used to measure the emission-line strength (§4.2). We fit the red-wing with a two-component model, a Gaussian core and Lorentzian wings, with the central wavelengths fixed together but allowed to vary slightly from the rest wavelength of C iv. We allow the strength and width of the two components to vary independently and fit to the red-wing taking care to avoid those regions of the spectrum contaminated by broad He ii λ1640 and O iii λ1663 emission. The measured width is taken to be the FWHM of the composite fit. If the measured FWHM<3500 km s$^{-1}$, then the object meets the criterion for the formation of an observable ghost feature.

For our 21 ghost-candidates with z>2.15, only 12 (57%) have FWHM (C iv) < 3500 km s$^{-1}$. In the remainder, those for which the C iv width can actually be measured (17 objects), 8/17 (47%) also meet this criterion. This fraction is similar to that found for our comparison sample where 12 out of the 20 objects (60%) for which C iv width measurements can be made, also meet this criterion (see Table 2 for details). Taking the average of all of the FWHM measured for the ghost candidates gives an average FWHM of 3345±842 km s$^{-1}$ which is similar to the upper limit proposed by Arav (1996) and to the average FWHM of C iv found for the comparison sample (3534±1100 km s$^{-1}$). A K-S test on these populations shows no significant difference between the ghost and comparison samples. The difficulty in fitting the C iv line in many of these objects results in large uncertainties in the estimated widths, however it is clear that several of our ghost candidates have emission that is wider than the 3500 km s$^{-1}$ upper limit proposed by Arav (1996). There are a number of possible explanations for this. Firstly, C iv may be a relatively poor surrogate for the width of Ly-α. Alternatively, our sample may suffer from contamination by objects in which the potential ghost feature is produced by a chance alignment of multiple absorption systems or through other mechanisms unrelated to radiative acceleration. If the potential ghost-features are indeed due to line-locking, then it may in-fact be possible to produce an observable ghost feature from emission-lines with widths in excess of 3500 km s$^{-1}$.

Figure 7. Comparison between the geometric mean composites formed from (i) 21 ghost-candidates with z > 2.15 (solid line), (ii) 25 BALs with featureless broad absorption troughs (dotted line), and (iii) non-BALQSOs from the DR5 QSO catalogue (dashed line).

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4.4 Strong N \( \text{v} \) broad absorption line

As described in §2, the ghost feature is produced by the increased radiation pressure on out-flowing N \( \text{v} \) ions by Ly-\( \alpha \) photons. Since in this model the N \( \text{v} \) ions scatter a significant fraction of the incident flux, strong N \( \text{v} \) absorption is a prerequisite.

In order to measure the strength of absorption due to N \( \text{v} \) we use a modified Balnicity index (Weymann 1991). We take the continuum to be equal to the mean flux between \( \lambda \lambda 1315-1330\text{Å} \), and require that the flux drops to below 90% of this value continuously for \( > 1000 \text{ km s}^{-1} \) between 0 and 7000 \text{ km s}^{-1} blue-ward of the N \( \text{v} \) emission line. We use the 7000 \text{ km s}^{-1} limit to avoid contamination by absorption due to Ly-\( \alpha \). Any object with a non-zero value for this measure is considered to show strong N \( \text{v} \) broad absorption.

Significant N \( \text{v} \) absorption is measured in all 21 objects from our ghost candidate sample whose redshift allows detection of N \( \text{v} \) absorption. Only 44% (11/25) of our comparison sample satisfy this criterion. The geometric composites of Figure 7, confirm that our ghost-candidate sample displays significantly stronger N \( \text{v} \) absorption on average than our comparison sample. Moreover, the broadly similar N \( \text{v} \) emission-line strengths of the ghost-candidate and comparison sample, emphasises the increased importance of N \( \text{v} \) absorption in the ghost-candidate spectra.

4.5 Little far-UV flux

Photo-ionisation models suggest that the far UV spectra of quasars contain a significant number of emission-lines between \( \lambda \lambda 2000 \) and \( \lambda 1000\text{Å} \) that will contribute to the radiation pressure on any BAL outflow (Korista et al. 1993). In order for a ghost feature to be observed the radiation pressure of Ly-\( \alpha \) on the N \( \text{v} \) ions in the outflow must be at least comparable in strength to the radiation pressure on all other ions in the outflow. This led Arav to suggest that the far-UV continuum must therefore be necessarily weak in objects showing ghost features. Absorption of far-UV photons both within the host galaxy as well as within our own galaxy preclude direct measurement of the far-UV continuum. However, note that the strength of the He \( \text{ii} \) \( \lambda 1640 \text{ Å} \) emission-line can be used as a surrogate for the far-UV ionising continuum. A strong He \( \text{ii} \) line suggests a similarly strong far-UV flux and vice-versa as this line is produced by photons with energies corresponding to \( \lambda 228\text{Å}(\approx 54\text{ eV}) \).

However, the He \( \text{ii} \) emission-line strength is notoriously difficult to measure even in high quality spectra. This is because of its close proximity to the \( \text{[O iii]} \)1663 emission-line, as well as its location near the red-wing of C \text{iv}, which may extend to relatively high velocities. Thus isolating the broad He \( \text{ii} \) component generally requires multi-component fitting (see e.g. Goad and Koratkar 1998) which without prior information (for example, variability data), is rather subjective.

Since the quality (in terms of S/N) of the individual spectra in both our ghost-candidate and comparison samples is relatively low, we do not attempt to fit to the individual line components. Instead, we use our non-BALQSO composite spectrum as a template for the region of interest, and scale each spectrum to this template, by minimising the residual flux in the region of interest. Our optimisation routine fits for the underlying continuum in both spectra, and adjusts for both redshift errors and the scale factor over the region of interest (nominally \( \lambda \lambda 1600-1680\text{Å} \)). Since both spectra are first normalised to the flux in the continuum band between \( \lambda \lambda 1700-1750\text{Å} \), if we assume that the He \( \text{ii} \) and \( \text{[O iii]} \) emission line strengths scale together, then the derived scaling factor between the ghost-candidate and non-BAL QSO spectra is a measure of the ratio of their He \( \text{ii} \) EWs. Figure 8 shows an example of a fit. In the top panel we show the non-BALQSO composite (solid line) and a ghost-candidate spectrum (dotted line). In the middle panel we show the spectra together with their continuum fits spanning the C \text{iv}-He \( \text{ii} \) region, while in the lower panel we show a close-up of the non-BALQSO composite and the scaled ghost-candidate spectrum after removal of the underlying continuum. The residual flux under the He \( \text{ii} \)-[O \text{ iii}] lines is indicated by the dot-dashed line. We caution that this fitting process is sensitive to (i) small redshift errors between the spectra, (ii) an appropriate choice of continuum bands (in general the choice of the continuum bands depend on the width of the C \text{iv} absorption trough, and most importantly (iii) the S/N of the spectra. Consequently the error on the scale factor is generally quite large. We have visually inspected the results of the fitting process for all of our ghost-candidate and comparison spectra to verify that the fitting procedure has converged correctly, adjusting the continuum bands, and region over which the spectra are scaled when necessary. In Table 1 we list the He \( \text{ii} \) scale factors, that is, the multiplication factor necessary to produce the same equivalent width in the ghost-candidate spectrum. A number less than 1 indicates that the ghost-candidate spectrum has larger equivalent width in the line in the region of He \( \text{ii} \) than the non-BALQSO spectrum. Conversely, numbers greater than 1 indicate that the ghost feature has a proportionately weaker He \( \text{ii} \) line. In order to determine error estimates on the derived scale factors, after determining a best-fit solution, we fix all parameters apart from the scale factor, and then minimise on this parameter only. We then calculate the 90% confidence interval on this one interesting parameter from the best-fit model by varying the scale factor until the \( \chi^2 \) value has increased by 2.71. Both the best-fit scale factor and its range (based on the 90% confidence interval), are given in Table 1 and 2.

For our sample of 21 ghost-candidates for which all criteria can be tested, 5 indicate a significantly weaker He \( \text{ii} \) EW, suggesting a weaker than average UV continuum. Only 5 objects show evidence for a stronger than average He \( \text{ii} \) EW. For the rest, there is no significant difference (within the errors) in their He \( \text{ii} \) EWs when compared to the non-BALQSO composite. For the 22 ghost-candidates for which only some of the criteria can be tested, 5 show evidence for a weaker than average He \( \text{ii} \) EWs, 6 indicate stronger than average He \( \text{ii} \) EWs, and the rest indicate no significant difference in the He \( \text{ii} \) EW when compared to the non-BALQSO composite. Thus only 11/43 (25%) of our ghost-candidate sample appear to satisfy the criteria for a weak UV continuum. Repeating this test on our non-ghost BALQSO comparison sample 8 objects indicate weaker than average He \( \text{ii} \) EW, 9 objects have stronger than average He \( \text{ii} \) EW, and 6 objects show no discernible difference in their He \( \text{ii} \) EW relative to the non-BALQSO composite. For the remaining
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4.6 Supplementary requirements - the width of the ghost feature

If we ignore the likely complex interaction between the Ly-α photons and Nv ions (i.e. we assume the optical depth in the flow is effectively constant with velocity), then naively one might expect that the ghost-feature should be at least as broad as the Ly-α emission-line responsible for its formation. We note that in fact scattering is likely dominated by the line core where the optical depth is larger. By requiring that any observed ghost feature is at least as broad as Ly-α, we can further refine our ghost-candidate sample to leave only the best ghost-candidates. While the width of any ghost-feature is relatively easy to measure (unless the S/N is low), we are once again limited by the accuracy to which we can measure the width of Ly-α, as this emission is absorbed in the process by which the ghost is formed. Here we again make use of the width of the C IV emission-line (see §4.3) as a surrogate for the width of Ly-α. We isolate the ghost feature by removing the underlying absorption trough by fitting a simple function (cubic spline). We then fit a single Gaussian to the ghost feature to provide an estimate of its width. The measured widths are listed in Table 1. We find no correlation between the width of the ghost feature and the width of the C IV emission-line (Figure 9). Instead, we find that in the vast majority of cases the ghost feature is narrower than the C IV emission-line (the solid line in Figure 9 is FWHM(C IV)=FWHM(ghost).

If we require that the FWHM of the ghost feature matches that of the C IV emission-line to within 1500 km s\(^{-1}\), then 11/20 (for one object we are unable to make emission-line width measurements) of our ghost-candidates for which all ghost-formation criteria can be tested also match this criterion. For our remaining ghost-candidates 8/17 (5 objects have no emission-line width information) also match this criterion. Of the 11 candidates with similar ghost and C IV widths for which all the criteria are testable all 11 show Nv absorption, 10 show strong emission lines, 9 have narrow C IV emission but only 2 show evidence for weaker than average He II emission. Of these two one has C IV FWHM of 4040 km s\(^{-1}\) while the other fails the criteria for strong emission lines.

5 DISCUSSION

For the 43 objects in our ghost candidate sample, 21 are at large enough redshift to allow us to test all of the criteria necessary for the formation of an observable ghost feature. Of these 21/21 satisfy the condition for strong Nv absorption. 18/21 also satisfy the condition for strong intrinsic Ly-α emission. However, less than half of the ob-

Figure 8. An illustration of our method for estimating the He II strength. Upper panel – non-BALQSO composite (solid line) and an example ghost-candidate spectrum (dashed line). Middle panel – model fits to the underlying continua. Lower panel – non-BALQSO composite (solid line) and scaled ghost-candidate spectrum, after subtraction of the underlying continuum. The residual flux is indicated by the dot-dashed line.

Figure 9. FWHM (km s\(^{-1}\)) of the C IV emission-line and the ghost feature. The solid line shows FWHM(C IV)=FWHM(ghost).

Figure 9. FWHM (km s\(^{-1}\)) of the C IV emission-line and the ghost feature. The solid line shows FWHM(C IV)=FWHM(ghost).
projects (12/21) satisfy the condition for narrow emission-lines, and even fewer (5/21) show weaker than average He II EW. While 11/21 objects satisfy the first 3 criteria, no single object meets all of the requirements for the formation of an observable ghost feature. For the remaining 22 objects, only 3 objects pass 2 of the first 3 criteria, and of these all show stronger than average He II. Of the 5 objects which indicate weaker than average He II strengths, only one can be tested for any of the other criteria, in this case, the width of the emission-line, which it fails.

None of the objects in our ghost-candidate sample are present in the samples produced by Arav (1996) or Korista et. al (1993) due to differences in the redshift ranges over which they were constructed. North et al. (2006) identified 7 strong ghost-candidate spectra in DR3 of the SDSS. 6 of those objects are also in our sample of 43 ghost-candidates. The other, SDSSJ142050.34-002553.1, has an assigned redshift of 2.085 in DR5 compared to the 2.103 used by North et. al (2006) and is therefore rejected by our ghost zone cut. Only one of North et al.’s ghost zone final cut is of sufficient redshift to test all of the criteria for the formation of an observable ghost feature SDSS J110623.52-004326.0. This object fails the narrow emission-line requirement. For the other 5 objects, 3 fail the test for narrow emission-lines, and 4 fail the test for weaker than average He II EW.

For our non-ghost comparison sample 12/25 meet the criterion for strong N v absorption, 20/25 meet the requirement of strong Ly α, while 12/22 meet the narrow emission-line width constraint. 9/25 objects show evidence for weaker than average He II strengths. However, only 3 objects meet 3 out of 4 criteria, and none of these meet the weaker than average He II strength. Thus, none of the objects in our comparison sample meet all of the criteria necessary for the formation of an observable ghost feature.

A comparison between our ghost-candidate and non-ghost samples suggests that the main difference between them lies in the strength of the absorption, with our ghost candidate sample displaying more objects with strong N v absorption. Comparison of the geometric mean composite spectra of these two samples, and their ratio (Figure 13) dashed (ghost-candidate) and dotted (non-ghost comparison spectra) lines, indicates that the ghost-candidate composite shows significantly stronger absorption at lower velocities in all of the strong lines Ly-α, N v, Si iv and C iv.

In order to test whether peaks are more common within the ghost-zone than elsewhere, we repeat the ghost selection method using two "fake" ghost-zones (red-ward and blue-ward of the original ghost-zone), in a similar fashion to North et al. (2006). These zones are created in precisely the same way as the ghost-zone except that the red zone is centred at 4000 km s^{-1} while the blue zone is centred at 8000 km s^{-1} blue-ward of the C iv emission-line. Of the 258 single peaked objects, 82 have peaks within the "fake" red zone and 50 have peaks within the fake "blue-zone".

Since the original ghost-zone contained 60 objects with single peaks, the evidence for an excess of objects with peaks at a preferred velocity is weak. That is, single peaks within the ghost zone are no more likely than single peaks at other velocities.

We have also examined the link, if any, between the peaks within the C iv absorption trough and N v absorption. In order to select N v BALs we use a modified Balnicity index (Weymann 1991). We take the continuum to be equal to the mean flux between λλ1315–1330Å, and require that the flux drops to below 90% of this value continuously for > 1000 km s^{-1} between 0 and 7000 km s^{-1} blue-ward of the N v emission line. In order to perform this test we require objects with redshifts in excess of 2.15. From a sample of 1747 objects with z>2.15, we find 1258 N v BALs and 489 N v non-BALs. 27% (340) of the N v BALs show multiple troughs in their C iv absorption compared to only 15.5% (76) of the N v non-BALs. Similarly, 7.6% (95) of the N v BALs and only 3.1% (15) of the N v non-BALs show a single peak in the C iv absorption trough. Among the N v non-BALs we find : i) two objects with single peaks within the ghost-zone, ii) two objects with a single peak in the fake blue zone, and iii) no objects with a single peak in the fake red zone. For the N v BALs, we find : i) 26 objects with single peaks within the ghost-zone, ii) 14 with single peaks within the fake blue zone, and iii) 33 with single peaks within the fake red zone. While these results indicate a strong link between the presence of N v absorption and the mechanism responsible for producing features within the C iv absorption trough, line-locking between Ly-α and NV does not appear to be the dominant mechanism.

In summary, N v BALs are more likely to have multiple troughs within the C iv absorption than N v non-BALs (factor of 2). Further, N v BALs are also more likely to display single-peaks within their C iv absorption than N v non-BALs. Approximately 25% of the single peaked objects are located within the ghost-zone. However, similar numbers are found in both the blue and red fake ghost zones. Thus while strong N v absorption appears to be a strong requirement for the appearance of features within the C iv absorption trough of BALQSOs, there is no preferred velocity for the location of these features.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure10.png}
\caption{Composite spectrum made up of all our ghost candidates fit with a reddened DR5 composite(dotted) and a BALQSO composite (dashed).}
\end{figure}
Figure 11. Spectra of ghost candidates from the best-candidate sample for which all criteria can be tested.
Figure 12. Spectra of ghost candidates from the best-candidate sample for which all criteria can be tested.
Searching for evidence of radiative line driving

In an analysis of the largest sample of BALQSOs derived from DR5 of SDSS, we have identified 43 objects which show evidence for radiative driving, as indicated by the appearance of feature in the C\textsc{iv} absorption, and thought to be associated with the interaction between Ly-\(\alpha\) photons and N\textsc{v} ions. We have attempted to explore the reality of these ghost-features by testing the physically motivated criteria, as set out by Arav, for the formation of observable features via this mechanism. Of the 21 objects for which we can test all of the criteria, none satisfy all of the conditions necessary for the formation of an observable feature. Two of the criteria, the width of the driving line, and the strength of the UV continuum are particularly difficult to measure. Of the 5 objects that clearly pass the latter criteria, having weak He\textsc{ii}, 4 have widths that are marginally larger than the upper limit imposed by Arav necessary to produce strong ghost signatures, while the other appears to have only weak emission-lines. We recognise that because of the large uncertainty on the measurements of the He\textsc{ii} strength, 8 further objects from the sample of 21 could potentially satisfy all of the criteria necessary for ghost-formation. Addressing this issue will require higher S/N data than currently available for these objects.

However, taken at face value either the conditions necessary for line-locking to occur are less stringent than previ-ously proposed, or a large fraction of these objects are multi-trough interlopers masquerading as ghost-candidates. This possibility is supported by our finding that the 'fake' ghost zones bracketing the 'real' ghost zone contain comparable numbers of objects as the 'real' ghost zone. This suggests that the peaks observed within BAL troughs at the position of the ghost-zone are not a physical effect of radiative line driving, but are instead independent of any systematic velocity.

Since our analysis has shed real doubt as to the existence of Ly-\(\alpha\)-N\textsc{v} line-locking features, in the attached appendix we repeat for the interested reader, the sequence of tests by Korista et al. (1993) and re-investigate the incidence of double-trough phenomena in a large sample of BALQSOs. In summary, the results of these tests show that there is no strong evidence for an excess of double troughs bracketing the region of ghost-formation, and that the evidence for line-locking between Ly-\(\alpha\) photons and N\textsc{v} ions in BALQSO spectra is substantially lacking.

Figure 13. Upper-panel - composite ghost-candidate (solid line) and comparison (dashed line) spectra. Lower panel - ratio of ghost-candidate to comparison spectra.

6 SUMMARY OF RESULTS

In an analysis of the largest sample of BALQSOs derived from DR5 of SDSS, we have identified 43 objects which show evidence for radiative driving, as indicated by the appearance of feature in the C\textsc{iv} absorption, and thought to be associated with the interaction between Ly-\(\alpha\) photons and N\textsc{v} ions. We have attempted to explore the reality of these ghost-features by testing the physically motivated criteria, as set out by Arav, for the formation of observable features via this mechanism. Of the 21 objects for which we can test all of the criteria, none satisfy all of the conditions necessary for the formation of an observable feature. Two of the criteria, the width of the driving line, and the strength of the UV continuum are particularly difficult to measure. Of the 5 objects that clearly pass the latter criteria, having weak He\textsc{ii}, 4 have widths that are marginally larger than the upper limit imposed by Arav necessary to produce strong ghost signatures, while the other appears to have only weak emission-lines. We recognise that because of the large uncertainty on the measurements of the He\textsc{ii} strength, 8 further objects from the sample of 21 could potentially satisfy all of the criteria necessary for ghost-formation. Addressing this issue will require higher S/N data than currently available for these objects.

However, taken at face value either the conditions necessary for line-locking to occur are less stringent than previ-
### Table 1

| Object Name | Redshift | Strong N v BAL | Strong Ly α emission | Narrow emission-lines FWHM (km s$^{-1}$) | He II EW scale factor | FWHM Ghost (km s$^{-1}$) |
|-------------|----------|----------------|----------------------|------------------------------------------|----------------------|------------------------|
| 024514.93-004101.9 | 2.802 | ✓ | ✓ | X(3624) | X 1.06 (0.89–1.31) | 2646 |
| 080621.45+191441.0 | 2.272 | ✓ | ✓ | X(4307) | ✓ 1.58 (1.23–2.17) | 1785 |
| 083719.50-364145.4 | 3.416 | ✓ | ✓ | X(2807) | ✓ 2.67 (2.05–3.74) | 2005 |
| 084310.93+050640.1 | 2.409 | ✓ | ✓ | X(2690) | X 0.96 (0.85–1.11) | 1744 |
| 085104.05+051539.8 | 3.213 | ✓ | ✓ | X(4324) | ✓ 1.56 (1.31–1.93) | 1013 |
| 090430.49+343108.9 | 3.408 | ✓ | ✓ | X(4067) | X 0.89 (0.78–1.00) | 1696 |
| 092557.52+044035.9 | 2.266 | ✓ | ✓ | X(5219) | ✓ 1.41 (1.09–2.07) | 1248 |
| 093742.72+433531.2 | 2.258 | ✓ | ✓ | ✓ (2725) | X 1.00 (0.81–1.23) | 1125 |
| 094427.27+614424.6 | 2.337 | ✓ | ✓ | ✓ (2426) | X 0.76 (0.68–0.87) | 782 |
| 094434.85+431403.5 | 2.291 | ✓ | ✓ | ✓ (2504) | X 0.65 (0.55–0.72) | 1833 |
| 101844.45+540155.6 | 3.253 | ✓ | ✓ | ✓ (2729) | X 0.43 (0.37–0.53) | 2168 |
| 103450.21+33326.1 | 2.496 | ✓ | ✓ | X(3943) | X 1.41 (0.99–2.48) | 2185 |
| 105058.28+614406.0 | 2.797 | ✓ | ✓ | ✓ (2375) | X 0.60 (0.53–0.69) | 2896 |
| 110623.51+043260.6 | 2.443 | ✓ | ✓ | X(4040) | ✓ 3.35 (>1.82) | 771 |
| 114704.47+153243.3 | 3.081 | ✓ | ✓ | ✓ (3258) | X 0.89 (0.79–1.00) | 1313 |
| 131505.19+603716.4 | 2.530 | ✓ | ✓ | X(3970) | X 0.89 (0.73–1.14) | 944 |
| 134818.04+422805.1 | 3.066 | ✓ | ✓ | X(2146) | X 1.16 (0.93–1.51) | 2505 |
| 142244.45+382330.6 | 3.728 | ✓ | ✓ | ✓ (2723) | X 0.89 (0.79–1.00) | 1337 |
| 144032.04+060554.1 | 2.297 | ✓ | ✓ | ✓ (2520) | X 0.49 (0.44–0.55) | 1333 |
| 162657.47+405848.0 | 3.051 | ✓ | ✓ | ✓ (2138) | X 0.93 (0.79–1.05) | 1032 |

| Object Name | Redshift | Strong N v BAL | Strong Ly α emission | Narrow emission-lines FWHM (km s$^{-1}$) | He II EW scale factor | FWHM Ghost (km s$^{-1}$) |
|-------------|----------|----------------|----------------------|------------------------------------------|----------------------|------------------------|
| 005109.45-001636.3 | 2.036 | ? | ? | X(4850) | X 1.30 (0.94–2.00) | 2800 |
| 023252.80-003511.7 | 2.033 | ? | ? | X(4016) | X 0.94 (0.82–1.09) | 709 |
| 033048.50-002819.6 | 1.779 | ? | ? | X(3147) | X 1.13 (0.86–1.63) | 4395 |
| 081158.10+343624.1 | 2.106 | ✓ | ✓ | X(3217) | X 0.56 (0.49–0.64) | 1006 |
| 082006.65+522158.7 | 2.015 | ? | ? | X(4062) | ✓ 3.61 (2.62–5.72) | 2607 |
| 091109.46+410155.2 | 2.128 | ? | ? | X(3706) | X 0.96 (0.85–1.08) | 1055 |
| 091313.09+411014.2 | 1.737 | ? | ? | X(3729) | X 0.78 (0.69–0.89) | 1336 |
| 092221.25+084312.8 | 1.969 | ? | ? | X(3970) | X 0.91 (0.77–1.08) | 503 |
| 102908.06+365155.2 | 1.750 | ? | ? | X(3706) | X 0.96 (0.85–1.08) | 1055 |
| 110736.67+000329.4 | 1.741 | ? | ? | X(3706) | X 0.96 (0.85–1.08) | 1055 |
| 111255.70+040600.5 | 1.989 | ? | ? | X(3729) | X 0.78 (0.69–0.89) | 1336 |
| 113831.42+351725.3 | 2.118 | ? | ? | X(3943) | X 0.91 (0.77–1.08) | 503 |
| 122107.07+074432.0 | 1.900 | ? | ? | X(4062) | X 0.91 (0.77–1.08) | 503 |
| 132304.58+038586.5 | 1.827 | ? | ? | X(4153) | X 1.09 (0.95–1.28) | 2077 |
| 133428.06+012349.0 | 1.876 | ? | ? | X(3943) | X 0.91 (0.77–1.08) | 503 |
| 144843.82+43457.5 | 2.052 | ? | ? | X(3956) | X 0.89 (0.73–1.12) | 1046 |
| 141843.95+373750.8 | 1.782 | ? | ? | X(4245) | X 0.89 (0.73–1.12) | 1046 |
| 155505.10+442151.3 | 1.798 | ? | ? | X(4425) | X 0.89 (0.73–1.12) | 1046 |
| 160335.43+225612.9 | 2.079 | ? | ? | X(4245) | X 0.89 (0.73–1.12) | 1046 |
| 163231.60+294929.7 | 1.905 | ? | ? | X(4245) | X 0.89 (0.73–1.12) | 1046 |
| 170056.85+602639.7 | 2.123 | ? | ✓ | X(4708) | X 1.15 (0.99–1.35) | 1913 |
| 172001.31+612145.7 | 1.760 | ? | ✓ | X(2528) | X 1.73 (1.24–2.95) | 2034 |

Table 1. Our Ghost sample and the results of testing Arav’s criteria along with the FWHM of the ghost feature.

1 Objects identified by North et al 2006 as their best ghost-candidates, their Ghost Candidate Final Cut (GCFC).
2 Poor continuum fit.
3 He II absorbed.
4 He II too weak to be measured.
### Table 2

| Object Name         | Redshift | Strong N $\lambda$ BAL | Strong Ly $\alpha$ emission | Narrow emission-lines FWHM (km s$^{-1}$) | He II EW scale factor |
|---------------------|----------|-------------------------|----------------------------|------------------------------------------|-----------------------|
| 013724.43-082419.9  | 2.5663   | X                       | √                          | (3174)                                   | X 0.39 (0.35-0.44)    |
| 014648.52-001051.8  | 2.3853   | √                       | √                          | (2186)                                   | X 0.83 (0.77–1.38)    |
| 021219.54+141739.1  | 2.1902   | X                       | X                          | (6457)                                   | X 0.94 (0.82–1.18)    |
| 024413.76-000447.5  | 2.7925   | √                       | √                          | (3804)                                   | X 2.72 (>2.46)        |
| 031331.22-070422.8  | 2.7548   | X                       | ?                          |                                         | X 3.35 (2.43–5.56)    |
| 081906.14+394813.8  | 3.2071   | X                       | X                          | (4142)                                   | X 0.43 (0.39–0.47)    |
| 084348.68+455269.9  | 2.5821   | X                       | X                          | (4024)                                   | X 1.06 (0.89–1.30)    |
| 084554.24+423003.5  | 2.5568   | X                       | √                          | (2378)                                   | X 3.92 (>1.69)        |
| 090115.18+371822.8  | 2.6173   | X                       | √                          | (2322)                                   | X 0.30 (0.27–0.33)    |
| 093804.52+120011.4  | 2.2273   | X                       | X                          |                                         | X 2.03 (1.59–2.79)    |
| 095220.88+371622.9  | 3.0928   | √                       | √                          | (3331)                                   | X 0.80 (0.66–1.00)    |
| 101324.20+064900.3  | 2.7675   | √                       | X                          |                                         | X > 4.07              |
| 101420.52+325931.9  | 2.3935   | X                       | √                          | (3256)                                   | X 0.41 (0.37–0.45)    |
| 104245.48+365642.2  | 2.8545   | √                       | √                          | (2235)                                   | X 0.44 (0.40–0.50)    |
| 110928.51+092403.8  | 2.5153   | X                       | √                          | (3432)                                   | X 0.49 (0.43–0.55)    |
| 111437.25+503445.9  | 2.2075   | X                       | X                          |                                         | X > 3.63              |
| 115901.75+065619.0  | 2.1906   | X                       | √                          | (3180)                                   | X 1.02 (0.79–1.43)    |
| 135559.03+002413.7  | 2.3438   | X                       | √                          | (3180)                                   | X 1.30 (1.11–1.53)    |
| 135912.20+450338.1  | 2.2794   | X                       | √                          | (3802)                                   | X 0.95 (0.68–1.58)    |
| 141225.35+041951.9  | 2.3882   | X                       | √                          | (4748)                                   | X 0.72 (0.60–0.89)    |
| 143559.60+034153.7  | 2.4646   | X                       | √                          | (4003)                                   | X 1.05 (0.85–1.32)    |
| 164148.19+233225.2  | 2.5061   | X                       | √                          | (2347)                                   | X 1.12 (1.00–1.46)    |
| 165816.78+231653.7  | 2.5753   | X                       | √                          | (6305)                                   | X 1.88 (1.26–3.66)    |
| 214113.05+035545.8  | 2.2329   | X                       | √                          | (3099)                                   | X 0.49 (0.43–0.54)    |
| 223841.88+142154.9  | 2.2898   | √                       | √                          | (2488)                                   | X 0.47 (0.43–0.52)    |

**Table 2.** As for Table 1, indicating our comparison sample of 25 objects selected to have broad absorption and no ghost-features and the results of testing Arav’s criteria for ghost formation.
Figure 14. Ghost candidates for which only some of the criteria can be tested.
Figure 15. Ghost candidates for which only some of the criteria can be tested.
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REFERENCES

Arav, Nahum and Li, Zhi-Yun, 1993, ApJ, 427, 700
Arav, Nahum and Li, Zhi-Yun and Begelman, Mitchell C., 1994, ApJ, 432, 62
Arav, Nahum and Begelman, Mitchell C., 1994, ApJ, 434, 479
Arav, Nahum and Korista, Kirk T. and Barlow, T. A. and Begelman, Mitchell C., 1995, Nature, 376, 576
Arav, Nahum, 1996, ApJ, 465, 617
Becker, R. H. and Gregg, M. D. and McMahon, R.G. and White, R. L. and Helfand, D. J., 1997, ApJ, 479, L93
Becker, R. H. and White, R. L. and Gregg, M. D. and Brotherton, M. S. and Laurent-Muehleisen, S. A. and Arav, N., 2000, ApJ, 538, 72
Blandford, R. D. and Payne, D. G., 1982, MNRAS, 199, 883
Bottorff, M., Korista, K.T., Shlosmann, I., Blandford, R.D., 1997 ApJ 479, 200.
Brotherton, M.S. and van Breugel, W. and Smith, R. J. and Boyle, B.J. and Shanks, T. and Croom, S. M. and Miller, L. and Becker, R. H., 1998, ApJ, 505, L7
Brotherton, M.S. and de Breuck, C. and Schaefer, J.J., 2006, MNRAS, 372, L58
Chelouche, D. and Netzer, H., 2001, MNRAS 326, 916.
Elvis, Martin, 2000, ApJ, 538, 72
Emmering, R.T., Blandford, R.D., and Shlosman, I. 1992, ApJ 385, 460.
Ferrarese, L. and Merritt, D., 2000, ApJ, 539L, 9
Gebhardt, K. et al., 2000, ApJ, 543L, 5
Gibson, R. et al., 2009, ApJ, 692, 758
Goad, M. and Koratkar, A., 1998, ApJ, 495, 718
Hall, P. et al., 2002, ApJS, 141, 267
Knigge, C. and Scaringi, S. and Goad, M. and Cottis, C., 2008, MNRAS, 386, 1426
Korista, Kirk T. and Voit, G. M. and Morris, Simon L. and Weymann, Ray J., 1993, ApJS, 88, 357
Korista, Kirk T. and Voit, G. M. and Morris, Simon L. and Weymann, Ray J., 1993, ApJS, 88, 357
Murray, N.; Chiang, J.; Grossman, S. A.; Voit, G. M. 1995 ApJ 451, 498.
North, Matthew and Knigge, Christian and Goad, Mike, 2006, MNRAS, 365, 1057
OGLE, P. M. and Cohen, M. H. and Miller, J. S. and Tran, H. D. and Goodrich R. W. and Martel, A. R. , 1999, ApJ, 125, 1
Pei, Yichuan C., 1992, ApJ, 395, 130
Pounds, K., 2003a, MNRAS, 345, 705
Pounds, K., 2003b, MNRAS, 346, 1025
Pounds, K. and Reeves, J., 2009, MNRAS, 397, 249
Proga, D., Stone, J. M., Kallman, T.R. 2000 ApJ, 543, 686.
Proga, D. 2007, in The Central Engine of Active Galactic Nuclei, ed. L.C. Ho, & J.-W. Wang, ASP Conf. Ser., 373, 267.
Reichard, T.A. et al., 2003a, AJ, 125, 1711
Reichard, T.A. et al., 2003b, AJ, 126, 2594
Scannapieco, E. and Silk, J. and Bouwens, R. , 2005, ApJL, 635, L13
Scaringi, S. and Cottis, C. and Knigge, C. and Goad, M. , 2009, MNRAS, 399, 2231
Schmidt, G. D. and Hines, D. C., 1999, ApJ, 512, 125
Shlosman, I., Vitello, P. A., and Shaviv, G. 1985, ApJ 294, 96.
Sprayberry, D. and Foltz, C.B., 1992, ApJ, 396, 487
Tremaine, S. et al., 2002, ApJ, 574, 740
Trump, Jonathan R. et al., 2006, ApJ, 165, 1
Turnshek, D. A., 1994, ApJ, 280, 51
Ulrich, M., 1989, A&A, 220, 71
Vilkojoki, E. Y.; Irwin, M. J. 2000 MNRAS 321, 4.
Weymann, Ray J. and Morris, Simon L. and Foltz, Craig B. and Hewett, Paul C., 1991, ApJ, 373, 23
Wilkes, B., 1984, MNRAS, 207, 73

APPENDIX A: ON THE REALITY OF THE DOUBLE-TROUGH PHENOMENA

Since the criteria by which observable ghosts are formed appears less stringent than has previously been claimed, we have performed a series of sanity checks to test whether ghost-features and double-troughs in general, are not simply a result of the random superposition of multiple absorption systems. The tests performed are similar to those described in Korista et al. (1993), though we note that our parent BALQSO sample is considerably larger and thus the quality of the statistics is a significant improvement over previous work.

A1 Random sampling

In the first test we compute the geometric mean residual intensity spectrum (the ratio of the geometric mean BALQSO composite divided by a geometric mean non-BALQSO composite spectrum) from two random samples (without replacement) taken from the BALQSO catalogue of Scaringi et al. (2009) (Figure A1, sample 1 (solid line), sample 2 (dashed line). These samples (consisting of 1776 objects each) were generated by sorting the BALQSO catalogue into RA order, and then selecting even-numbered objects for the first sample, and odd-numbered objects for the second sample. The mean residual intensity spectra for both samples are virtually indistinguishable, aside from a small difference (~15%) in the residual intensity in the velocity range 3900–7800 km s^{-1} blue-ward of line centre, which intriguingly, is precisely where the purported ghost feature should be found. We have checked to see whether there exists an excess of ghost-candidate spectra in either sample, and find that the ghost candidates are spread evenly amongst both samples, with 21 in sample A and 22 in sample B. While there are small apparent differences in the mean residual intensity spectrum in the region of the ghost-feature, neither sample shows convincing evidence of a double-trough feature.

To explore these findings further, we have attempted to address whether there exists any substantive evidence for absorption components at preferred velocities. If ghost features are relatively common, we would expect an excess abundance of peaks within the absorption trough at velocities 5900 km/s blue-ward of line centre. To address this question we have performed two additional tests. In these tests we work with fluxes instead of residual intensities to avoid complications introduced by uncertainties in fitting the C IV emission-line blue-ward of line centre. In the first,
At approximately 15,000 km/s. As with the previous test, varying the bin widths between 500-1500 km/s does not significantly alter the results.

These additional tests suggest that for the general BALQSO population, there is no substantive evidence that there exist preferred velocities for the location of peaks within the broad absorption troughs of BALQSOs. Thus if ghosts are real they are certainly rare, as was first suggested by Arav. We note that the incidence of single peaks (or double troughs) in our sample 258/3552 (7%) is significantly smaller than that found by Korista et al. (1993, 22%), likely a result of the small number statistics of this earlier study.

Figure A1. Geometric mean composite residual intensity spectrum of two randomly selected BALQSO samples (without replacement).

We take the LVQ BALQSO sample of Scaringi et al. 2009, and compare the fluxes in 3 adjacent velocity bins (A, B and C) each with widths of 1000 km/s, where B is the reference bin and A and C represent the adjacent bins. Sliding these bins from a velocity of 0-30,000 km/s blue-ward of C\textsc{iv} rest, we record the number of times the mean flux in the central bin (bin B) exceeds the mean flux in adjacent bins A and C by more than 3 $\sigma$. To show the effects of selecting different bin-widths over which the fluxes are measured, we repeat this exercise for bin widths of 500 and 1500 km/s. The results of this procedure are shown in Fig A2 (upper left panel). The distribution of peaks shows a prominent peak at zero velocity, which we associate with the location of the C\textsc{iv} emission-line peak. Ignoring this feature, the peak distribution is a generally smooth function of velocity with no indication of an excess number of peaks at 5900 km/s blue-ward of line centre. The same analysis performed on our ghost candidate sample, displays a similar peak at zero velocity, and in addition further peaks at around 6000 km/s and 11,000 km/s. While the numbers of peaks at higher velocities is only marginally less than that at 5900 km/s, visual inspection of our ghost candidate sample suggest that the significance of these secondary peaks is rather low.

We have also performed a variation on this method in which instead of measuring the intensities within each bin, we measure the mean gradient of the intensities within each of the bins. A peak is recorded if and only if the gradient in bin A is positive, the gradient in bin A is greater than the gradient in bin B, the gradient in bin B is greater than gradient of C, and the gradient in bin C is negative. Figure A2 lower panels shows the result of this test. Again, the peak at zero velocity we associate with the peak of the C\textsc{iv} emission-line. Thereafter the distribution of the locations of the peaks follows a smooth broad function with a maximum.
Figure A2. Distribution functions showing the incidence of peaks as a function of velocity blue-ward of CIV rest wavelength (see text for details). Upper left panel - LVQ BALQSOs, peak distribution functions (solid line 500 km/s bins, dotted line 1000 km/s bins, dashed lines 1500 km/s bins. Upper right panel - as for upper left for the ghost-candidate sample. Lower panels, as above except now using slope comparisons.
A2 Appearance of double-troughs at other velocities

In the second test we verify whether there exist associated troughs (via line-locking) at velocities other than systemic. We do this by aligning each spectrum according to the location of the red-edge of the first BAL trough and thereby search for evidence of a bi-modal distribution of sub-troughs. Here, the red-edge is defined as in Korista et al. (1993) to be where the residual intensity falls below 0.75 and remains below this level for more than 1000 km s$^{-1}$. The resultant geometric mean residual intensity spectrum is shown in Figure A3. As one might expect, the residual intensity is somewhat steeper at lower velocities, a result of aligning the first troughs in velocity space. However, the remainder of the spectrum is a smooth function of velocity, with no indication of additional sub-troughs. Thus, as with Korista et al. (1993) we find no evidence for line-locking features at velocities other than systemic.

Unlike Korista et al. (1993) the distribution of velocities of the first trough peaks at velocities between 1500–2000 km s$^{-1}$ blue-ward of line-centre, thereafter the number of objects contributing to each velocity bin shows a smooth linear decline. Thus while there appears a preference for the onset of BALs toward lower velocities, there is no indication of other preferred blue-ward velocities. This again suggests that the incidence of the double-trough signature among the BALQSO population as a whole is generally low. We note that the distribution of redshifted troughs are similarly peaked toward lower velocities and may indicate a preferred launch radius for the out-flowing gas.

A3 K-S test

In our third test, we compute the mean residual intensities in 3 separate velocity bins, one centred on the expected location of any ghost-feature, the other taken from bins either side of this feature, ie. velocity bins at 4000–5000 km s$^{-1}$, 5500–6500 km s$^{-1}$ (the reference bin),
and 10000–11000 km s\(^{-1}\) respectively. We then use the Kolmogorov-Smirnov (KS) test to check whether the distribution of residual intensities within each of these velocity bins belongs to the same population as the reference bin. The residual intensity spectra we use for this test are (i) the total sample of BALQSOs from Scaringi et al. (2009), the randomly selected samples 1 and 2 described above, our Multi-trough sample from rejection cut 2, our single peak sample from rejection cut 3 and our candidate ghost sample. The results of this test are presented in Table A1.

Table A1 gives the probability that the K-S statistic of the sub-trough with the reference trough (i.e. the ghost zone) would be exceeded by chance if they were drawn from the same population. That is, lower K-S probabilities indicate more significant differences between the chosen velocity bin and the reference bin. Our analysis shows that only for our ghost sample do both sub-troughs 1 and 2 indicate significant differences from the reference bin (K-S probabilities less than 0.1%). This is as expected, since members of this sample were selected precisely because they showed significant ghost-like features. The single peak sample shows no evidence that the residual intensity of the ghost zone is drawn from a different population to that of sub-trough 2. This suggests that the single peak sample does not have a systematic peak and that the position of peaks within the absorption is random and unrelated to Ly-α-N v line locking.

A4 A Monte Carlo test for ghosts

Korista et al. (1993) described one further test for an excess of double-trough features bracketing the Ly-α-N v line-locking region, which we repeat here for completeness. In this Monte Carlo simulation, we test how frequently the depth of the double-trough structure is exceeded by a random arrangement of residual intensity differences among each of the 3 velocity bins (see Korista et al. 1993 for details). For each spectrum, we can form 6 residual intensity differences from 3 velocity bins. For each spectrum in our BALQSO catalogue we randomly pick 2 from the 6 possible residual intensity differences and calculate their mean value, i.e. an average residual intensity difference. We then define \( < D >_{\text{random}} \) to represent the mean of these average intensity differences across our BALQSO sample. \( < D >_{\text{random}} \) is then compared to \( < D > \), formed by averaging the mean residual intensity differences between sub-troughs 1 and 2 with the reference bin, again averaged across our whole sample. \( < D > \) can take on any value between ±1. Values of \( < D > \) near +1 indicate a strong double-trough structure. Conversely, a value of \( < D > \) near –1 indicates a strong trough at the position of the reference bin. Values near zero are indicative of a smooth trough passing through the velocity bins.

To test how frequently a double-trough structure having a contrast at least as large as that observed in the sample mean could arise by chance, we repeat this process 10,000 times for each sample, and determine the number of times \( < D >_{\text{random}} \) exceeds \( < D > \), normalised to 10,000. The results of these simulations are shown in Table A2.

Since we only find strong evidence for the double-trough structure within our ghost zone sample (chosen for precisely that reason), we conclude that there is indeed no strong evidence for an excess of objects with sub-troughs bracketing the ghost-zone among the BALQSO population at large. Indeed, the high probabilities found for both the LVQ sample and for the multi-trough sample, strongly suggest that multi-trough features are randomly distributed in velocity. We are therefore conclude that many of the objects previously identified as strong ghost-candidates in previous studies may simply be MT interlopers masquerading as ghosts due to the chance alignment of multiple un-associated absorption systems.

A5 SDSS J101056.68+355833.3: Si IV ghost?

This is an object selected for our comparison sample as it shows no hint of a ghost feature within the deep broad C iv absorption. The spectra is shown in Figure A6 along with the flux in velocity space relative to C iv and Si iv showing clearly the potential ghost feature in the Si iv absorption. SDSS J101056.68+355833.3 meets the criteria for strong emission due to C iv and N v emission exceeding 100% of the continuum flux at their peak, shows clear N v absorption, has C iv FWHM measured as 3483 km s\(^{-1}\) and an EW of He i measured to be 3.58±0.82 Å. These measurements place this object very close to the boundary on several criteria and it would not be surprising to see a ghost feature in this object. While no ghost feature can be seen in the C iv trough, there is a clear feature within the Si iv trough (~6200 km s\(^{-1}\)) within the ghost zone. Due to the greater separation of the Si iv doublet(1933 km s\(^{-1}\)) in comparison to the C iv doublet(498 km s\(^{-1}\)) a ghost feature in the Si iv would be expected to be wider and weaker. This larger doublet separation is the reason for the wider ghost zone in the Si iv BAL trough. The absence of a C iv feature could be due to an extremely high optical depth in the flow such that the
Figure A6. SDSS J101056.68+355833.3: A possible Si iv ghost showing no evidence of a C iv feature along with close ups in velocity space of the C iv (middle) and Si iv (top) ghost regions. Vertical lines represent the ghost zone.

Flow remains optically thick even with the decrease in optical depth caused by the acceleration due to N v ions. However, the absorption troughs of C iv and Si iv look very similar with the exception of the potential ghost feature suggesting the optical depths are similar. There is a slight hint of an additional feature within the Si iv at ~8200 km s⁻¹ which is in the appropriate region to be due to the lower wavelength doublet feature from Si iv.