# The nature of quasar outflows

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Scientific field of application: quasars

# 1 Abstract

Quasar outflows impact on the evolution of supermassive black holes, their host galaxies, the surrounding IGM, and cluster cooling flows. Observationally, outflows are detected as broad or narrow absorption lines (BALs, NALs) in the UV. Progress in understanding outflows has in part been slow because few quasars were known at high enough redshifts for their rest-frame UV spectra to be studied from the ground.

This situation has changed dramatically with the advent of SDSS, which discovered an unprecedentedly large number of high-redshift BAL/outflow quasars whose rest-frame UV spectra can profitably be studied with ground-based 4-m telescopes (i.e. not just with Keck or HST).

We propose timely exploitation of SDSS by using the complementary optical and IR instruments of the WHT, TNG and NOT to address the following questions, crucial for assessing the importance of quasar outflows in feedback scenarios:

- **How far from the quasar nuclei do the observed outflows typically lie? What are the implied kinetic luminosities?**
- **What are the physical conditions in the outflows? How are BALs related to NALs?**
- **Does radiation pressure play a role in accelerating the outflows to velocities of up to 0.2 c?**
- **What do time-variations in the depth of the absorption lines tell us about the spatial structure of the outflows?**
- **Why are radio-loud BALs rare?**

We will make publicly available, via an electronic archive, an atlas of the reduced BAL-quasar spectra obtained during the project.

Our similar proposal for the international time last year was highly ranked (second place).

# 2 Number of nights requested at each telescope

| Telescope/instrument | dark | grey | bright | TOTAL |
|---|---|---|---|---|
| WHT/ISIS spectroscopy | 5 | 4 | 7 | 16 |
| TNG/NICS spectroscopy | 0 | 0 | 7 | 7 |
| NOT/ALFOSC spectroscopy | 5 | 3 | 4 | 12 |
| Mercator/MEROPE imaging | 0 | 0 | 4 | 4 |
| TOTAL | 10 | 7 | 22 | 39 |

i.e. we request $\sim$ half of the nominal ITP allocation on each of the WHT, TNG and NOT. A breakdown of the time request by project is given in Section 6. The SDSS targets lie mainly at $8 < \mathrm{RA} < 17$ h, so observing time in the first half of the year is preferred. All observations will be carried out by the applicants.

# 3 Background

## 3.1 Quasar outflows

There has recently been growing recognition of the potential importance of quasar outflows for the growth of super-massive black holes (Silk & Rees 1998; Cattaneo et al 2005; Hopkins et al 2005, 2006; Begelman et al 2006; Hu et al 2006), enrichment of the intergalactic medium (Cavaliere 2002; Levine & Gnedin 2005; Li et al 2006), galaxy formation (Haiman & Bryan 2006), evolution of the host galaxy (Scannapieco & Oh 2004; Granato et al. 2004, Di Matteo et al 2005), cluster cooling flows (Nipoti et al 2005; Thacker et al 2006, Nayakshin et al 2007), magnetisation of cluster and galactic gas (Furlanetto & Loeb 2001; Kronberg et al. 2001) and the luminosity function of quasars (Wyithe & Loeb 2004). **However, for want of a better alternative, these theoretical studies use the physical properties of the wind as free parameters in models with few observational constraints.** To assess the impact of quasar outflows on the processes mentioned above, it is essential to determine the physical properties of real quasar winds, in particular their kinetic luminosity as a fraction of the total quasar luminosity.

## 3.2 BAL quasars

Outflows are manifested most spectacularly as broad absorption lines (BALs) in the blue wings of prominent emission lines (e.g. CIV) in 10 – 20% of optically-selected quasars, tracing outflow velocities up to $\sim 0.2$ c (Hewett & Foltz 2003). The absorption troughs can be highly structured, but are smooth compared with thermal line widths. $\sim 20\%$ of BALs are detached from the corresponding emission line by several thousand kms$^{-1}$ (see Fig. 1 and Korista et al 1993 for examples). The blue and red edges of the BAL absorption trough are often relatively abrupt, spanning $\sim$ 100s kms$^{-1}$. These distinctive features would be hard to reconcile with absorption by individual clouds, but are consistent with the line of sight to a BAL quasar intersecting an outflow which is not entirely radial, e.g. an outflow which initially emerges perpendicular to the accretion disk, and is then accelerated radially (Murray et al 1995, Elvis 2000). NV 1240-Å BALs often absorb part of the Ly$\alpha$ emission line, so the BAL region must typically lie outside at least some of the broad emission-line region (BLR), i.e. $> 0.1$ pc from the quasar nucleus, but otherwise the distance is unknown within several orders of magnitude. BALs are generally saturated (optical depth $\sim$ few) but non-black, implying partial covering of the nuclear regions (or infilling of the absorption troughs by scattered light). Saturation means that column densities cannot be measured directly from apparent absorption depths.

The most prominent BALs are due to high-ionisation species, particularly Li-like ions with one electron in the outer orbit: CIV 1549 Å, SiIV 1400 Å, NV 1240 Å. Quasars whose absorption is dominated by these are known as high-ionisation BALs (HiBALs). $\sim 15\%$ of BAL quasars also show absorption by lower-ionisation species, such as MgII 2798 Å and AlIII 1858 Å, and are known as LoBALs. FeLoBALs are a small subset of the LoBALs showing absorption by FeII and FeIII. Absorbers similar to quasar BALs are seen in Seyfert 1 galaxies, albeit with lower outflow velocities, typically $<$ few hundred kms$^{-1}$ (see contributions in Crenshaw, Kraemer & George 2002).

No self-consistent physical model yet exists for the acceleration of the outflowing gas in BAL quasars, or, if the filling factor is small (many small clouds), for its confinement. Possible mechanisms for the acceleration include radiation pressure, pressure

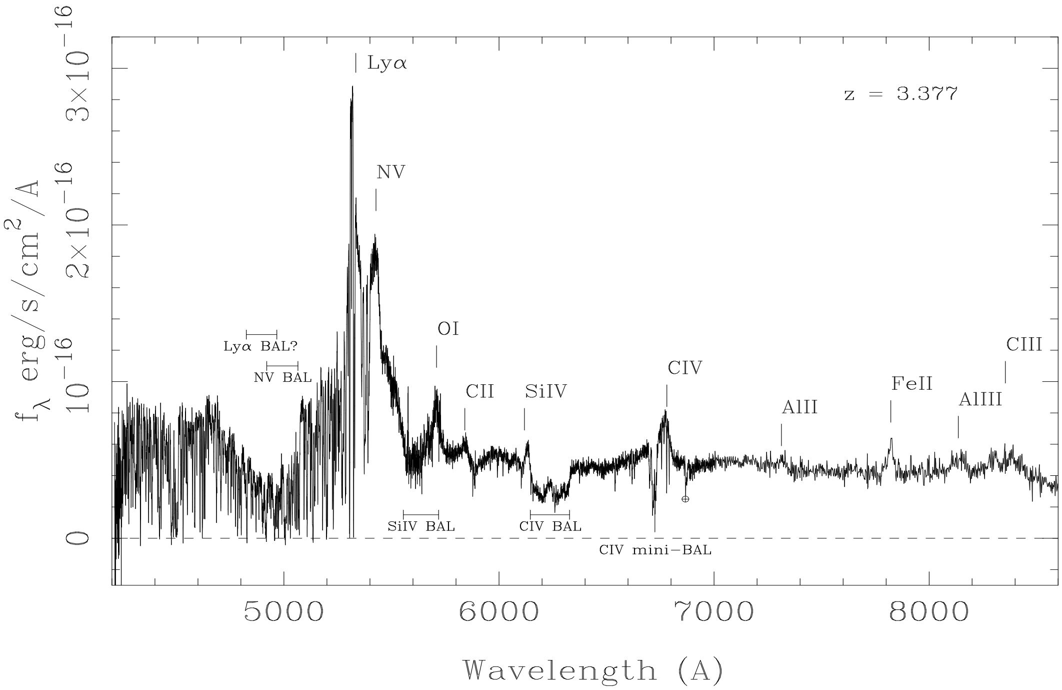


Figure 1: Medium-resolution spectrum of a BAL quasar, r = 18.5, obtained with the ISIS spectrograph on the WHT (the points redward of 7200 Å are from the SDSS spectrum). The mini-BAL just blueward of the CIV emission line ranges in velocity -2200 – -3400 kms$^{-1}$. It is also detected in NV ($\approx$ 5370 Å) and in OVI ($\approx$ 4490 Å). From Benn et al (2005).

from cosmic rays or centrifugally-driven magnetic disk winds (de Kool 1997). Radiation pressure is a popular candidate, but it's not clear how it can be sustained without over-ionising the gas.

BAL outflows are crucial for understanding the physics of AGN because:
(1) They probe the inner regions of the accretion disk, and probably play a role in the accretion process by helping to shed angular momentum;
(2) Many BAL quasars are super-Eddington accretors, offering a unique perspective on the changes in disk geometry (e.g. thickening) with accretion rate;
(3) The highly-energetic BAL outflows are probably related to other outflows seen in AGN (e.g. in radio galaxies).

Hypotheses about the nature of BAL quasars differ mainly in the emphasis placed on the role of orientation. On the one hand, BALs may be present in all quasars but are intercepted by only $\sim 10-20\%$ of the lines of sight to the quasar (Weymann et al 1991, Elvis 2000), e.g. within the walls of a bi-funnel centred on the nucleus. Alternatively, BALs may arise in a physically distinct population of quasars, e.g. newborn quasars shedding their cocoons of gas and dust, or quasars with unusually massive black holes, or with unusually high accretion rates (Briggs, Turnshek & Wolfe 1984, Boroson & Meyers 1992).

Until recently, very few radio-loud BAL quasars were known. This changed with the advent of the FIRST Bright Quasar Survey (FBQS, Becker et al 2001), but few BALs are known with log $R^* > 2$ (radio-loudness $R^* = S_{5GHz}/S_{2500A}$, Stocke et al 1992). Becker et al (2001) estimated that BALs are four times less common amongst quasars with log $R^* > 2$ than amongst quasars with log $R^* < 1$. Hewett & Foltz (2003) note that optically-bright BAL quasars are half as likely as non-BALs to have $S_{1.4GHz} > 1$ mJy. The reason for the dependence of BAL fraction on $R^*$ is unknown, but it may reflect the higher ratio of X-ray to UV luminosity in radio-louder objects, which could over-ionise the gas, reducing the velocity to which line-driven winds can be accelerated (Murray et al 1995). Becker et al (2000) found that radio-selected BAL quasars have a range of spectral indices, which suggests a wide range of orientations, contrary to the favoured interpretation for optically-selected quasars. Radio-loud BALs tend to be compact in the radio, similar to GPS or CSS sources, and GPS/CSS sources are thought to be the young counterparts of powerful large-scale radio sources (O'Dea 1998). This supports the alternative hypothesis that BALs represent an early phase in the life of quasars (Gregg et al 2000).

In Boroson's (2002) scheme for the classification of AGN, based on a principal-component analysis of AGN properties, the different observed types correspond to different combinations of $L/L_{Eddington}$ (luminosity as a fraction of Eddington luminosity) and $dM/dt$ (the accretion rate). BAL quasars occupy one corner of this space, with $L/L_{Eddington} \sim 1$, similar to narrow-line Sy1 galaxies, but with a much higher accretion rate. The BAL quasar accretion rates are similar to those of radio-loud quasars, but with larger $L/L_{Eddington}$ (and lower-mass black holes). In Boroson's scheme, the rare radio-loud BAL quasars may be objects with extremely high accretion rates.

Lamy & Hutsemékers (2004) carried out a principal-component analysis of 139 BAL quasars with good-quality spectra and/or polarisation measurements. They found that most of the variation is contained in two principal components. The first is dominated by a correlation between BALnicity index (a measure of the BAL equivalent width, Weymann et al 1991) and the strength of the FeII emission, and may be driven by the accretion rate. The second is due to the fact that BALs with PCyg profiles (i.e. absorption just blueward of the emission line, small detachment velocity), are more polarised than those with detached BALs. Detachment is thought to correlate with orientation, with the more detached BALs being seen if the angle of the line of sight to the disk is larger.

To summarise, key outstanding questions about BAL quasars, which impinge on our understanding of the physics and evolution of AGN in general, and of the effects of outflows on their environment, are:
- How far from the nucleus does the absorbing gas lie? What is the kinetic luminosity of the outflow?
- How are the outflows accelerated to such high velocities without over-ionising the gas?
- Are BAL quasars intrinsically unusual, or selected by orientation?
- Why are radio BAL quasars rare?

To address these questions, detailed measurements of physical conditions within the outflows are required, together with a systematic statistical comparison of the properties of radio and non-radio BAL quasars.

### 3.3 Mini-BALs and NALs as probes of physical conditions

The blending of saturated absorption features in the BALs themselves precludes measurement of the column densities, which are required to constrain the ionisation balance, the distance of the absorber from the quasar and the physics involved in accelerating the outflows. However, some quasars show additional narrow absorption lines (mini-BALs and NALs) with velocity widths small enough (FWHM $<$ 2000 km/s) that multiplets of individual ions can be resolved. This means that the covering factor and true optical depth of the absorber (and hence column densities, metallicity and ionisation parameter) can be determined independently (Barlow & Sargent 1997, Arav et al 1999). The partial covering, variability and smooth absorption troughs indicate that mini-BALs are intrinsic outflows like those seen in BALs, but with the advantage that in some cases the covering factor and optical depth can be measured as a function of velocity. Mini-BALs are thus particularly useful for constraining physical conditions in the outflow.

Using mainly HST, Keck and VLT, high-resolution spectra of intrinsic mini-BAL and NAL absorbers have been obtained in several individual quasars (e.g. Arav et al 1999, Arav et al 2001, Churchill et al 1999, deKool et al 2001, D'Odorico et al 2004, Ganguly et al 2003, Gupta et al 2003, Hall et al 2003, Hutsemékers, Hall & Brinkmann 2004, Petitjean et al 1999, Srianand et al 2000, Srianand et al 2001, Srianand et al 2002). These analyses established the intrinsic nature of the absorbers, and showed the importance, when measuring column densities, of taking into account saturation and the limited covering factor. The analyses also implied that the absorbers lie close to the quasar nucleus, but there are few actual measurements of distance.

In summary, intrinsic NALs and mini-BALs are excellent probes of the abundances and physical conditions in outflows close to the nuclei of quasars, with each object providing a fresh perspective.

## 4 Motivation for this proposal

Studies of *individual* outflow quasars have raised intriguing questions (Section 3) about the nature of the outflows. Until recently, a shortage of suitable targets precluded systematic surveys to address these questions. However, SDSS (Abazajian 2004) has now provided spectra of large numbers of BAL/ouflow quasars, and some of these have a combination of properties which makes them ideal for the kind of analysis described in Section 3.3.

SDSS is a unique resource, comparable in scope and impact to the Palomar sky survey. Competitive exploitation by 4-m and smaller telescopes depends crucially on starting follow-up work now. Here we propose to observe overlapping sub-samples of SDSS BAL/outflow quasars with the complementary optical and IR spectrographs available on La Palma, to investigate several interrelated questions (Section 5). Relatively-large allocations of time on three facilities are required to carry out several closely-related programmes, so this project is well-suited to ITP.

## 5 Objectives of this proposal

We summarise below the specific objectives of the proposal. These can be achieved at considerably less cost in telescope time than individual proposals towards each objective, because of the overlap between the required samples for objectives 5.2 - 5.4, and because of the flexibility offered to match observing conditions to programme (e.g. good seeing is a particular advantage for objective 5.1).

For most of the objectives, the aim is to determine the shape of the distribution of a given parameter, so the sample sizes we've quoted are the minima to do this with useful resolution along that parameter (e.g. sufficient to allow splitting into sub-samples along that parameter), bearing in mind (1) that in some cases the distribution is a priori completely unknown (e.g. objective 5.1) and (2) that in some cases the cost in terms of telescope time rises rapidly with increasing sample size (i.e. increasing magnitude limit).

### 5.1 How far from the nucleus are typical quasar outflows, what is $L_k$?

The impact of quasar outflows on the evolution of supermassive black holes, their host galaxies and the IGM depends on the kinetic luminosity of the outflow $L_k = 4\pi\Omega D N_H m_p v^3$. $\Omega$ is the fraction of the total solid angle occupied by the outflow, $D$ is the distance of the outflow from the central source, $N_H$ is the total hydrogen column density, $m_p$ is the mass of the proton and $v$ is the velocity. $N_H$ and $D$ are uncertain over several orders of magnitude (Arav 2003). As discussed in Section 3.3, measuring true column densities (cm$^{-2}$) requires solving for covering factor and optical depth using multiple absorption lines from a given ion. This is illustrated in Figs. 2, 3 and 4 (and Benn et al 2005). Given the column densities of more than one ion, the ionisation parameter $U$, and $N_H$, can be estimated. To obtain the distance $D$, the density $n_H$ (cm$^{-3}$) is required. This can best be estimated from the column densities (derived as above) of meta-stable states such as FeII$^*$, FeIII$^*$ and NiII$^*$. Different lines are sensitive to different ranges of $n_H$. Outflows showing troughs from meta-stable levels are rare, perhaps because they are viewed along a line of sight grazing the accretion disk (Hall et al 2003), and the same outflow seen from a higher inclination (the vast majority of cases) may have a higher ionisation equilibrium, showing only SiIV, CIV and higher ionised species. However, analysis of meta-stable transitions is currently the *only* way known to measure $L_k$. The best-constrained measurement so far is by de Kool et al (2001), but this is for only one object. SDSS now includes several relatively-bright ($r < 18$) quasars showing large numbers of FeII absorption lines which are sufficiently velocity-resolved (400 - 700 km/s) that a covering-factor analysis can be carried out with spectroscopic resolution $R \approx 10000$. An example is shown in Fig. 5.

We propose to obtain spectra of the 12 brightest such quasars in SDSS ($r < 18$), in order to determine the distribution of distances (and $L_k/L_{bol}$). Resolution $R \approx 10000$ (30 km/s, to get 10 - 15 resolution elements across the absorption troughs) and S:N = 30 (Petitjean et al 1999, Srianand et al 2000, Arav et al 2001, Gupta et al 2003, see also Fig. 3) are required to carry out the proposed covering-factor analyses.

### 5.2 What are the physical conditions in BAL outflows?

The analysis above will reduce the orders-of-magnitude uncertainty in the measured outflow distances and densities, but is restricted to those rare outflows showing absorption from meta-stable states, and only a few of these are associated with features formally defined as BALs. To complement this analysis, we propose the first *systematic* study of a relatively unbiased sample of BAL quasars exhibiting velocity structure on the scale of the SDSS spectral resolution (170 km/s), i.e. mini-BALs. This will allow us to carry out similar analyses for the commonly-observed OVI, NV, SiIV and CIV absorbers, deriving covering factors, true column densities and ionisation parameters U.

We propose high-S:N, high-resolution spectroscopy of 40 bright ($r < 19$) BALs. This will increase by a factor of $\sim 5$ the number of BAL quasars for which such analyses have been carried out, providing statistically-significant sub-samples to allow comparison of the properties of the BALs (velocity width, detachment velocity, covering factor) with those of embedded (or distinct) NALs/mini-BALs, which will shed light on the relationship between them, e.g. similar covering factor may imply shared location. In addition, we will be able to explore, for the first time, the

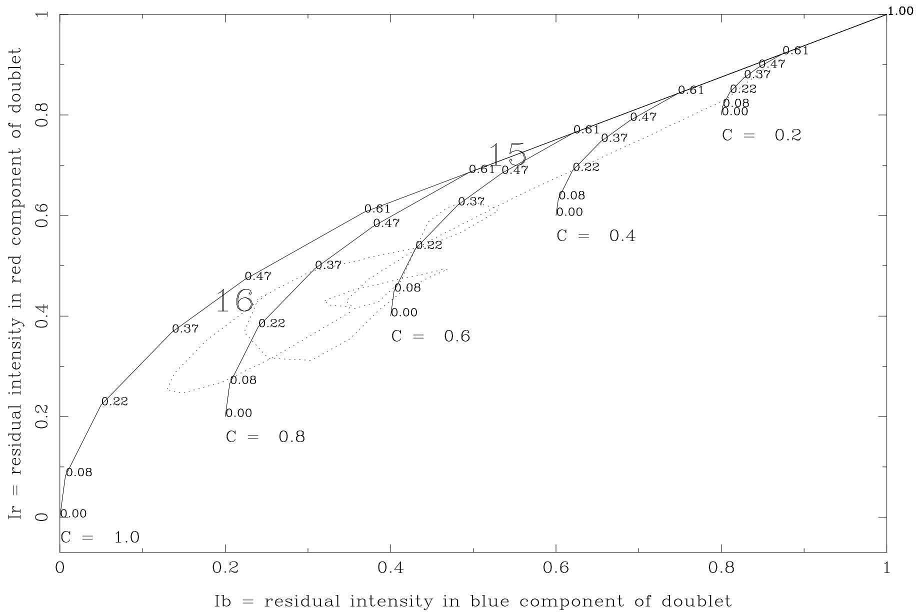


Figure 2: Estimation of covering factor $C$ and optical depth $\tau$, from the residual intensities in the two components of a doublet line. Each solid curve traces for a given covering factor $C$, the expected variation with $e^{-\tau}$ (the small numbers on the plot give $e^{-\tau}$ for the blue component of the doublet), of the residual fractional intensities $I_b, I_r$ in the two components of a doublet with expected optical depth ratio 2:1 (e.g. CIV 1548.2 / 1550.8 Å, NV 1238.8 / 1242.8 Å, OVI 1031.9 / 1037.6 Å). By way of example, the dotted line traces the $C$, $\tau$ solution plotted in Fig. 4.

relationship between the NAL/mini-BAL and radio properties. E.g. if radio jets usually entrain gas which would otherwise be seen as BAL/NAL flows, it is plausible that one might see evidence of this difference in those NALs that are detected in radio-BAL quasars.

We require spectroscopy of OVI, Ly$\alpha$, NV, SiIV and CIV absorption, for 40 objects. As in Section 5.1, resolution $R \approx 10000$ (30 km/s, a factor 5 better than SDSS) is required. S:N = 20 suffices for the covering-factor analysis of these broader features.

### 5.3 How important is radiative acceleration?

As noted in Section 3, several possible mechanisms have been suggested for accelerating BAL outflows to such high velocities. One possible signature of the most popular candidate, line-radiation pressure, is absorption-absorption line-locking. This can occur when light of the wavelength required for a given transition in one cloud (e.g. CIV 1550.78 Å) is absorbed by ions in a cloud closer to the quasar, with different velocity and undergoing a different transition (e.g. CIV 1548.20 Å). This reduces the line radiation pressure on the shadowed cloud, and the cloud may lock at a velocity difference from the shadowing cloud corresponding to the wavelength difference of the two transitions. In general, several lines will contribute to the total radiation pressure on a cloud, but if this approximates the net force in the opposite direction (gravity, and perhaps drag), the effect of line-locking in one line can be significant (Korista et al 1993).

A few convincing examples of line-locking in BAL quasars are known, e.g. $z = 1.8$ quasar 1303+308 (Foltz et al 1987, Vilkovskij & Irwin 2001) and $z = 2.9$ quasar 1511+091 (Srianand et al 2002). The former includes several SiIV absorption doublets spaced by the separation of the two components of the doublet (i.e. a 'picket fence'). Plausible examples of line-locking have also been noted in the published spectra of a few other quasars (Srianand et al 2000, Ganguly et al 2003, Gupta et

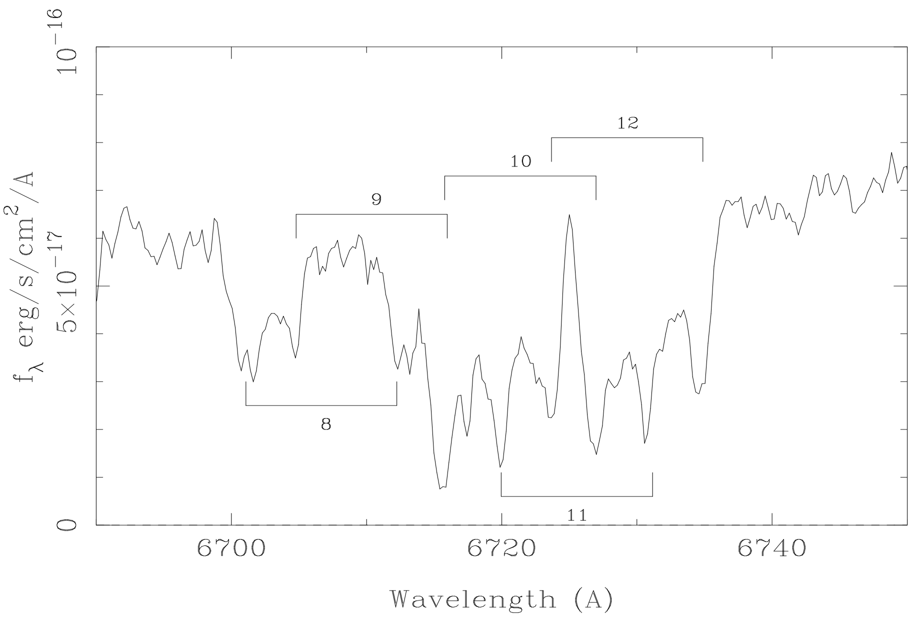


Figure 3: WHT ISIS spectrum of a CIV mini-BAL, instrumental resolution 0.8 Å, or 36 kms$^{-1}$, from Benn et al (2005). The ticks indicate the wavelengths of the CIV doublets (1548.20, 1550.78 Å).

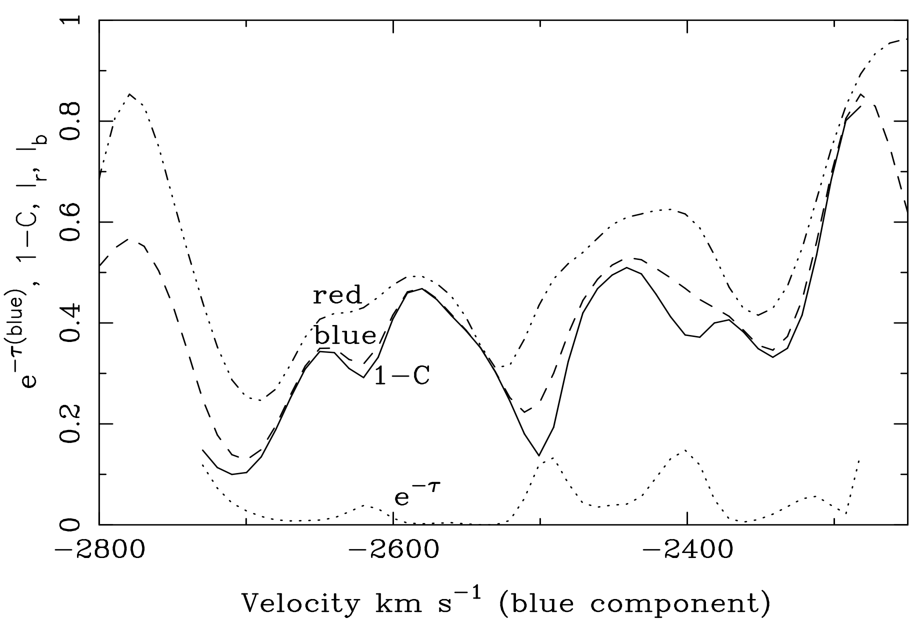


Figure 4: Covering factor $C$ (the solid curve shows 1-$C$) and optical depth $e^{-\tau}$ in the blue component of the CIV doublet (dotted curve), derived as a function of velocity for the mini-BAL shown in Fig. 3 (using Fig. 2). The residual intensities $I_b$ and $I_r$ from which $C$ and $e^{-\tau}$ were derived are also shown (dashed and dot-dashed curves 'blue' and 'red' respectively). For $v <$ -2500 km/s, the shape of the CIV mini-BAL is dominated by changes of the covering factor with velocity, rather than by changes in optical depth. For $v >$ -2500 km/s, the optical depth, and hence the column density, can be measured. From Benn et al (2005).

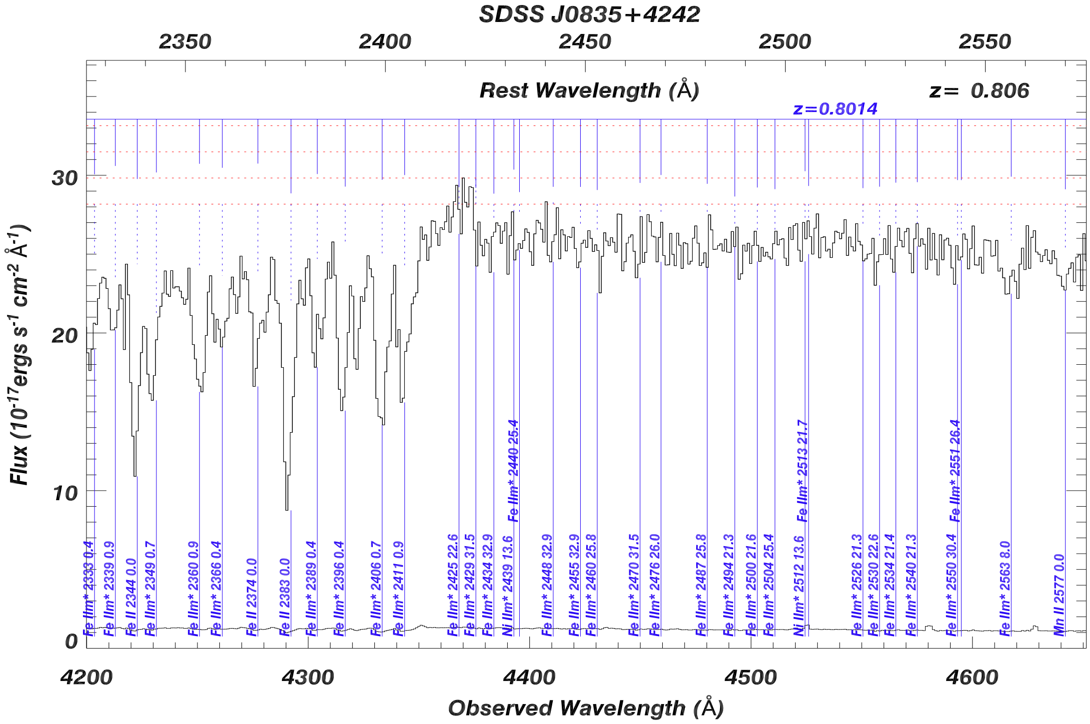


Figure 5: Part of an SDSS spectrum of a $z = 0.806$, $r = 18$ quasar, showing many absorption lines by meta-stable Fe at $z = 0.8014$. The lines are labelled with wavelength in Å, and energy level in 1000 $\text{cm}^{-1}$.

al 2003, see also Fig. 3), and the 'ghost of Ly$\alpha$' (North et al 2005) also provides evidence for line-driven radiation pressure. This suggests that line-locking is present in roughly 10 - 20% of BAL quasars studied at the appropriate resolution.

The small number of appropriate targets has until now precluded a systematic search for line-locking between absorption features in BAL quasars. Here we propose to carry out *the first systematic search*, in spectra of 100 $r < 19.5$ quasars, increasing by a factor $\sim 5$ - 10 the number of NAL features studied in BALs, expecting to discover $\sim 10 - 20$ examples of line-locking. This is sufficient to test with considerable confidence the null hypothesis that the observed examples of line-locking are chance coincidences. If it is confirmed that line-locking exists, this implies that radiation pressure is important in accelerating the gas, and we will determine the fraction of systems affected, and the ions most commonly responsible. For those objects which show line-locking, we will integrate long enough to measure column densities, and thus identify the physical conditions in which line-locking is most frequently found.

We require spectra of 100 objects for this objective, but the observations under objective 5.2 above furnish 40, so we need to observe spectra of only an additional 60. We need to detect Ly$\alpha$, NV, SiIV, CIV with resolution 1-Å ($\sim 50$ km/s) to resolve most NALs, and S:N per resolution element = 10 to achieve sufficient wavelength precision to exclude chance coincidences.

## 5.4 Why does the depth of the absorption lines vary with time?

Changes in the depths of absorbers appear to be common ($>$ 20% of BALs, Barlow et al 1992, Hall et al 2002) but the samples so far studied are small. These changes are likely due to transverse motion of clouds across the line of sight, or perhaps to changes in the ionisation parameter at the outflow, caused by variations in quasar luminosity. If the former, then the timescale of variations, combined with a plausible assumption about the diameter of the ionising source, yields an estimate of the transverse velocity of the wind.

We propose spectroscopy and imaging of the 200 brightest suitable BALs observed by SDSS ($r < 19.5$), expecting to detect variations in absorber depth in $> 40$ of these. These 40 will be observed again 1 year later, to provide a third measurement of the absorber depth. With this sample size, we will be able to determine the distribution of amplitude variations. Comparison of the photometric light curves with the spectroscopic variation will tell us whether the variation is due to winds crossing the line of sight, or to changes in the ionising continuum, and in the former case will yield a rough estimate of the distribution of wind velocities, which can be compared with the observed radial velocities.

These spectra can also be used to search for changes in velocity, so far reported in only one quasar (1303+308, Vilkovskij & Irwin 2001, $\Delta = 55$ km/s over 5 years rest-frame) but potentially constraining strongly the distance of the outflow from the quasar nucleus, if the wind is being steadily accelerated outwards. For clouds accelerated to 0.1 c over a few 10s of pc at $z = 3$, the expected velocity change over an observed-frame year is a few km/sec.

We require spectra of 200 objects for this objective, but the observations under objectives 5.2, 5.3 above furnish 100, so we need to observe spectra of only an additional 100. We require resolution $\sim 3$ Å (to match SDSS), and S:N $\approx 10$ per resolution element (given the changes seen by e.g. Barlow et al 1992). We also require 4-epoch imaging of $\sim 40$ of these quasars, with S:N $\sim 50$ to measure any changes in continuum luminosity.

### 5.5 Why are radio-loud BALs rare?

As noted in Section 3, radio-loud BALs may be rare because the physical structure (of the accretion disk and BLR) which gives rise to radio jets, may not be conducive to the formation of BAL flows, and vice versa. E.g. it has been suggested that the outflows which give rise to BALs might in radio-loud objects be entrained by the radio jets. It is thus likely that there are differences in the optical properties of radio BAL quasars and non-radio BAL quasars, which may yield important clues about the nature of the outflows.

For example, the frequency of LoBALs amongst radio BAL quasars appears to be higher, $\sim 30\%$ (Becker et al 2000, 2001, Menou et al 2001) than amongst non-radio BAL quasars, $\sim 15\%$. The FeII 'small blue bump' (rest-frame 2000 – 4000 Å), whose strength is a possible signature of a thickening accretion disk at high accretion rates (Boroson 2002, Lamy & Hutsemékers 2004) might also be more prominent in radio BAL quasars (which in some models are extreme accretors). Differences in the structure of the accretion disk and/or BLR could also give rise to differences in the mean dust extinction.

To complement the SDSS optical spectra, we therefore propose low-resolution IR spectroscopy 0.9 – 2.4 $\mu$ of the optically-brightest 20 radio BAL quasars, $r < 19.5$, and a matched comparison sample of the 20 optically-brightest non-radio BAL quasars, $r < 19$ (we will separately obtain detailed radio observations, see Section 5.6). This will allow us to compare for radio and non-radio samples the mean: (1) FeII-emission strength; (2) strength of the MgII 2800-Å absorption (characteristic of LoBAL quasars); (3) continuum shape over a large wavelength range (factor of 4), constraining differences in extinction (using also H$\alpha$/H$\beta$ where possible). We will use TNG/NICS with the AMICI prism, which covers 0.8 – 2.4 $\mu$ and has uniquely high throughput. The spectral resolution is 50, which, with S:N = 20 per resolution element, suffices for all three suggested comparisons (see e.g. the spectra obtained by Maiolino et al 2004b). We propose observing 20 quasars in each sample, to have a reasonable chance of detecting a significant difference in any of the above parameters, given the intrinsic spread, e.g. we will be able to place a limit $\Delta A_V < 0.2$ mag on any difference in extinction due to SMC-type dust.

In addition to the above, the spectra obtained under Section 5.2 above will allow us to investigate another intriguing possible difference between radio and non-radio BALs. Richards et al (2002) found that the number density $n(z)$ of CIV NALs in radio BAL quasar 0747+2739 is unusually high, even at high velocities ($\sim 0.1$ c) relative to the quasar. Richards et al suggested that these NALs might be remnants of past BAL outflows. With the high-S:N, high-resolution large-wavelength-coverage spectra proposed under Section 5.2, we will greatly increase the search space for such NALs.

### 5.6 Related radio/sub-mm observations

We note that the optical observations proposed here are complemented by an independent campaign of radio observations of BAL quasars recently begun by us, triggered in part by our discovery that the most radio-luminous BAL quasar known, 1624+3758, has the second-highest rotation measure of any extragalactic source, rest-frame 18000 rad $m^{-2}$ (Benn et al 2005).

The aim is to test whether the properties of radio BAL quasars are consistent with the unification-by-orientation hypothesis, or if on the other hand they suggest that radio BALs are predominantly young AGN (see Section 3). The observations include multi-frequency radio polarimetry to determine rotation measures, spectral shapes and synchrotron ages, and high-resolution VLBI observations to investigate where the strong Faraday rotation arises. Observations have already been made for this project with the Effelsberg, WSRT (search for HI absorption), VLA and VLBA radio telescopes.

We have also begun a programme to measure the mass and temperature of the dust in BAL quasars with JCMT/SCUBA.

## 6 Observations required / technical feasibility

The targets are all SDSS quasars, with those for goals 5.2-5.5 being drawn from the 1200 $r < 19$ quasars with $2.5 < z < 4.5$ (to ensure visibility of the UV resonance lines). Of these, $\sim 10\%$, i.e. $\sim 120$ exhibit BAL-like features (including mini-BALs) with velocity structure at the SDSS resolution limit. SDSS includes an additional 1200 quasars with similar properties, but with $19 < r < 19.5$. Approximately 10% of the BAL quasars have FIRST radio counterparts $S_{1.4GHz} > 1$ mJy.

Below we tabulate the time required to address each of the goals outlined in Section 5, assuming an average 8 hours per night on-sky (9 hours of astronomical night, less 10% acquisition, configuration and calibration overheads for the optical spectroscopy). We will minimise instrument-configuration changes (and data-reduction overheads) by grouping observations by redshift.

| Goal | $N_{qso}$ | $r <$ | $R$ | S:N | Instrument | Moon | Nights |
|---|---|---|---|---|---|---|---|
| 5.1 | 12 | 18.0 | 10000 | 30 | WHT/ISIS spectroscopy | G/B | 5 |
| 5.2 | 40 | 19.0 | 10000 | 20 | WHT/ISIS spectroscopy | D | 5 |
| 5.3 | 60 | 19.5 | 6000 | 10 | WHT/ISIS spectroscopy | G/B | 6 |
| 5.4 | 100 | 19.5 | 2000 | 10 | NOT/ALFOSC spectroscopy | D/G/B | 12 |
| | 40 | 19.5 | | 50 | Mercator/MEROPE imaging | B | 4 (4-epoch) |
| 5.5 | 40 | 19.5 | 50 | 20 | TNG/NICS/Amici spectroscopy | B | 7 |

ISIS provides high-resolution spectroscopy and broad wavelength coverage (2-arm spectrograph), and ALFOSC and NICS/Amici have lower resolution but very high throughput.

In the above table, S:N is the signal-to-noise per resolution element. To fit within the available space, we have omitted detailed S:N calculations, but these can be provided on request.

During observing, we will monitor the S:N in real time, using quick-look data-reduction software available at the telescope. In the event of poor observing conditions (or less than the full amount of time being granted), we will observe fewer objects rather than compromise on S:N.

## 7 Project management

If granted time, we will organise the work, and review progress, through regular team meetings, beginning with a planning meeting 3 months before observations commence.

We have at our disposal a total of $\sim 8$ staff years for the project: 0.5 for planning and observing, 3 for data-reduction, the remainder for analysis and publication.

Most members of the team are experienced observers, familiar with standard spectroscopic data-reduction procedures. We will observe in teams of 2 – 3 people, i.e. individual team members will each spend a total of $\sim 6$ nights observing. Two of us (CRB, MP) are resident on La Palma, and are familiar with WHT and TNG instrumentation.

The data reduction, using iraf, is straightforward, and we plan to complete it within 12 months of observing. The reduced spectra will be made available immediately to the whole team via the electronic archive.

We plan to publish as separate papers the results from each of the investigations outlined in Section 5. By splitting the work amongst sub-teams, we expect to submit the results for publication within 2 years of the relevant observations being completed. We will organise a conference (probably on La Palma) at the end of the period to further disseminate the results.

The atlas of reduced BAL spectra will be made publicly available through an electronic archive.

In addition to funding from host institutions, we have financial support for travel, meetings etc. during 2006-2008 through grant AYA2005-00055 from the Spanish Ministerio de Educacion y Ciencia (grant-holder IGS, project title: 'Observational cosmology: radio-selected quasars at $z > 2.5$').

The PhD studies of one of us (FJ) will be based in part on the observations obtained via this proposal.

## 8 Use of previous ITP time

RC and IGS were involved in an earlier, unrelated, ITP project (PI Perez-Fournon) to follow up the European Large Area ISO Survey. The key results were: (1) Identification of optical counterparts of MIR, FIR and radio sources in 60% of the survey area, and discussion of the spectral energy distribution of the extragalactic sources in terms of starburst and AGN dust torus models, and of the source counts (Rowan-Robinson et al, 2004). (2) Discovery of a hyperluminous infrared quasar at z=1 which is one of the very few luminous IR objects with X-ray emission (Morel et al 2001).

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