Broad Absorption Line Quasars and the Radio-Loud/Radio-Quiet Dichotomy

ZDENKA KUNCIC

Department of Physics and Astronomy, University of Victoria, Victoria, BC V8W 3P6, Canada

Received 1999 April 6; accepted 1999 May 6

ABSTRACT. The observation that the extremely broad, blueshifted absorption troughs which characterize broad absorption line quasars (BALQs) occur exclusively in radio-quiet quasars (RQQs) suggests that this class of active galactic nuclei (AGN) may offer important clues to the radio-loud/radio-quiet (RL/RQ) dichotomy in quasars. Interestingly, there is also substantial observational evidence for similar, but lower velocity, intrinsic absorption outflows in some Seyfert galaxies and radio-loud quasars (RLQs) as well. Theoretically, however, it is difficult to interpret this broad range of mass ejection phenomena in the context of the standard model for BALQs. Thus, a new model is considered here in which the thermal gas producing the blueshifted absorption troughs is associated with a poorly collimated outflow of weakly radio-emitting plasma—in essence, a weak jet. This model provides an appropriate framework not only for assessing the possible connection between the BAL phenomenon in RQQs and related intrinsic absorption outflows in stronger radio sources and in less luminous sources, both of which are known to possess jetlike radio structure, but also for understanding the RL/RQ dichotomy in light of recent observations which indicate that at least some RQQs possess central engines that are capable of producing weak versions of the powerful radio jets characteristic of RLQs. In the context of a weak jet model for BALQs, it is shown that observational constraints on the physical properties of the radio-emitting plasma are consistent with other theoretical arguments suggesting that the differences amongst RL and RQ sources can be attributed to jets with intrinsically different physical properties. Similarly, theoretical constraints on the physical properties of absorbing clouds embedded in weak jets are shown to be consistent with the properties directly inferred from the observed BAL troughs. Most importantly, however, it is argued that a weak jet model provides a successful explanation for the anticorrelation between the terminal velocity of the absorption outflow and the radio power of the quasar.

1. INTRODUCTION

In the framework of the standard accreting black hole paradigm, unified models have been remarkably successful in explaining the apparently disparate subclasses of active galactic nuclei (AGN) as simply different facets of what are otherwise more or less fundamentally identical systems (Antonucci 1993; Urry & Padovani 1995). Despite this success, however, a single, orientation-based scheme cannot explain the bimodality in the radio luminosity distribution (Kellermann et al. 1989; Miller, Rawlings, & Saunders 1993), so that a true, “grand unification” scheme for all AGN still remains elusive. One clue to understanding the radio-loud/radio-quiet (RL/RQ) dichotomy and unifying AGN is the possibility that radio-quiet quasars (RQQs) are capable of producing radio jets, albeit much weaker, smaller scaled versions of the powerful, highly collimated jets that are characteristic of radio-loud quasars (RLQs). Some observational evidence supporting this possibility has emerged: high-resolution imaging of RQQs has revealed that the radio emission of at least some of these objects originates within a compact, nonthermal source directly associated with a central engine which appears qualitatively similar to those in RLQs (Blundell & Beasley 1998a; Kukula et al. 1998); a correlation between radio and [O III] λ5007 luminosities, indicative of the presence of jets, has been measured in not only in Seyfert galaxies (Whittle 1985), but also in some quasars (Miller et al. 1993); and finally, a significant number of radio-intermediate quasars (RIQs) have been found, possessing radio emission which is unusually high for RQQs (but still below that of RLQs) and which has been attributed to weak beaming (Miller et al. 1993; Falcke, Sherwood, & Patnaik 1996), although this still remains unclear. But perhaps the most compelling evidence is the recent discovery of apparent superluminal motion in a RQQ (Blundell & Beasley 1998b). This is the first direct evidence for a fundamental similarity in the origin of radio emission in RLQs and RQQs.

Another observational clue to understanding the RL/RQ dichotomy may be provided by broad absorption line
quasars (BALQs). These sources, which comprise 10%–15% of optically selected quasars, are characterized by (rest frame) UV spectra with extremely broad (up to 30,000 km s⁻¹) and often deep absorption lines that are blueshifted with respect to their corresponding emission lines (chiefly resonance lines due to highly ionized species such as C iv, Si iv, and N v). According to the standard model (Weymann et al. 1991; and see Weymann 1997 for a recent review), these absorption troughs are formed in a narrow, quasi-equatorial outflow of numerous, dense (∼10⁶–10⁹ cm⁻³) cloudlets accelerated by line radiation pressure across a region ∼1 pc in extent. Although BALs have been detected only in RQQs (see, e.g., Weymann et al. 1991; Stocke et al. 1992), there are two intriguing findings which have yet to be explained: the statistically significant overabundance of BALQs amongst RIQs (Stocke et al. 1992; Francis, Hooper, & Impey 1993), and the recent discovery of “weak” BALs in a handful of RLQs identified by the FIRST survey (Brotherton et al. 1998). The BALs in these RLQs are “weak” in the sense that the profile widths of the absorption troughs (several thousand km s⁻¹) are noticeably narrower than those typically measured in BALQs and, similarly, the “balnicities” are much lower. Thus, as pointed out by Weymann (1997), there is an anticorrelation between the terminal velocity of thermal gas ejected from quasar nuclei and the radio power of the quasar. Note, however, that none of the RL BALQs appear to be powerful radio sources; all have a ratio, R* = radio-to-optical flux (K-corrected) satisfying 1 ≤ log R* ≤ 2.5, while the maximum flux density measured is no higher than 30 mJy at 20 cm. Nevertheless, even if these sources are found to more closely resemble RLQs with “associated absorbers” (Foltz et al. 1988), they can still provide important clues to the BAL phenomenon since there is evidence that at least some of the associated absorbers seen in RLQs (mainly steep-spectrum sources) are closely connected with the nucleus and may perhaps represent the low-velocity end of intrinsic absorption outflows in quasars (see, e.g., Barlow & Sargent 1997; Aldcroft, Bechtold, & Foltz 1997).

Similarly, narrow UV absorption features have also been detected in some Seyfert 1 galaxies, and these have been interpreted as a low-luminosity version of the BAL phenomenon in quasars. Moreover, some of these Seyfert galaxies (and a few quasars as well) exhibit “warm absorber” X-ray signatures, and there is growing evidence that the outflowing, absorbing material responsible for the BAL-like features is also responsible for the X-ray features (Crenshaw et al. 1999; Mathur, Wilkes, & Elvis 1998; Gallagher et al. 1999 and references therein). It is also interesting to note that some of the nearby AGN exhibiting nuclear absorption outflows (e.g., NGC 3516, NGC 4151, NGC 5548, Mrk 231) also exhibit the linear and extended radio structures that are often detected in Seyfert galaxies and that are believed to result from the outflow of radio plasma along axes determined by the dust torus obscuring the active nucleus (see, e.g., Baum et al. 1993). Indeed, such extended radio structures in Seyfert galaxies are generally interpreted as small-scale, low-power versions of the large-scale, powerful jets and lobes seen in radio galaxies and quasars (see, e.g., Ulvestad & Wilson 1989).

Although these observations suggest that nuclear absorption outflows comprise a dynamically important mass-loss component in AGN that can span a wide range of parameter space, they are difficult to interpret in the context of the standard model for the BAL phenomenon in RQQs. In this paper, the BAL phenomenon is examined in the context of a broader model in which nuclear absorption outflows are associated with poorly collimated, weak radio jets. This model provides a framework not only for examining the connection between BALs in RQQs and the weaker absorption features in stronger radio sources (the RL BALQ candidates) and in lower luminosity counterparts (Seyfert galaxies), but also for testing the hypothesis that all AGN possess jet-producing central engines and that jets with intrinsically different physical properties (e.g., radio power, bulk speeds) are at least partly responsible for the observed RL/RQ dichotomy. The model is qualitatively outlined in §2 and is then used to obtain observational and theoretical constraints on the relevant physical properties of nuclear absorption outflows in §§3 and 4, respectively, and the main results are summarized in §5.

2. A WEAK JET MODEL

In the model constructed here, a weak jet is defined as a poorly collimated outflow of radio-emitting plasma moving at a low bulk speed, with a corresponding bulk Lorentz factor Γ ≲ a few. Such an outflow may not necessarily satisfy the traditional criterion for the formal definition of “jet” (length-to-width ratio ≳ 4; Bridle & Perley 1984), nevertheless, it is useful to apply the jet description in order to determine the extent to which the RL/RQ dichotomy can be attributed to differences in jet properties, including the relative quantities of nonthermal and thermal plasma. Although the conditions under which jets form still remain poorly understood, recent theoretical results (Begelman 1998) indicate that a lack of self-collimation may be due to the absence of a relatively strong, stabilizing poloidal magnetic field component. Poorly collimated jets would lack a Doppler-boosted radio core and would therefore be observed as much weaker radio sources than highly colli-
mated jets. Thus, jet collimation plays an important role in the observed bimodality in the radio power distribution.

While it is physically plausible that all jets contain some thermal matter in the form of dense clumps (Begelman, Blandford, & Rees 1984), exactly how much is present, relative to the tenuous, synchrotron-emitting plasma, remains uncertain. Recently, Celotti et al. (1998) placed some constraints on the amount of comoving, thermal gas that could exist in the form of cool, dense clouds embedded within the powerful, highly beamed relativistic jets in RLQs and BL Lac objects. While it was concluded that such material could be present only in such energetically insignificant quantities so as to preclude observational detection, this need not necessarily be the case for thermal gas in mildly relativistic and subrelativistic jets in much less powerful sources. Indeed, it is argued here that the observational evidence for such jets is precisely the BAL phenomenon.

As discussed further in §3, the distribution of relativistic particles in such jets can be expected to extend down to thermal energies, so that the mean Lorentz factor, $\langle \gamma \rangle$, of emitting electrons is much lower than it is in more powerful jet sources. This in turn is reasonable to expect if in situ acceleration of particles to nonthermal energies (on subparsec scales) is also less efficient. Under such conditions, a continuous supply of fresh particles is required to replenish the “dead” particles that have radiatively cooled and to thereby maintain a constant radio flux. As shown by Ghisellini, Haardt, & Svensson (1998), electrons at the low end of their energy distribution can effectively thermalize via cyclosynchrotron self-absorption before escaping the source region on subparsec scales. On these scales, the resulting quasi-thermal electrons can then cool via inverse Compton scattering; the ratio of the cooling timescale to the escape timescale is $\sim r_{0.1pc} v_{0.1c} L_{45}^{-1}$ (where $r = 0.1r_{0.1pc}$ pc is the source size, $v = 0.1v_{0.1c}$ c is the bulk flow speed, and $L = 10^{45} L_{45}$ ergs s$^{-1}$ is the luminosity). The thermal gas can then cool further to temperatures well below the local Compton temperature ($\sim 10^7$ K) provided the gas density is sufficiently high for bremsstrahlung to become more efficient than inverse Compton cooling; the required densities are $\gtrsim 10^4 L_{45} r_{0.1pc} T^{-1/2}$ cm$^{-3}$. As will be shown in §4.2, this lower limit corresponds to the critical density discriminating between the nonthermal and thermal gas phases in an inhomogeneous jet. Thus, the local accumulations of condensed, thermal gas which arise as a result of rapid cooling and poor reacceleration could be identified as the progenitors of the absorbing cloudlets which emerge on $\sim$parsec scales. If this is indeed the case, then it provides a natural explanation for why the BAL phenomenon becomes increasingly rarer in more powerful radio sources, where presumably in situ particle acceleration is more efficient (see e.g., Weymann, Turnshek, & Christiansen 1985 for other possible origins, including entrainment).

Since velocities measured from the observed blueshifted troughs in BALQs are typically no more than $\sim 0.2c$, either the dense cloudlets could be moving slower than the bulk velocity in a mildly relativistic jet, or they could be comoving with the radio-emitting plasma in a subrelativistic jet. If such cloudlets comprise a significant kinetic energy flux component in a mildly relativistic jet and are moving at subject speeds with a velocity $v_{\text{BAL}}$, then the total energy flux is given by (see, e.g., Bridle & Perley 1984)

$$ \frac{L_{\text{jet}}}{r^2 \Omega} \approx \left( \frac{\langle \gamma \rangle \rho_{\text{jet}} c^2 + \frac{\Gamma \beta_{\text{jet}}^2 \varepsilon}{8\pi}}{\frac{L}{8\pi}} \right) \beta_{\text{jet}} c + \frac{1}{2} \varepsilon \rho_{\text{cld}} v_{\text{BAL}}^3, $$

(1)

where $\Omega \approx 2\pi \phi^2$ is the total solid angle subtended by jets on either side of the nucleus ($\phi$ is the jet opening angle), $\Gamma \beta_{\text{jet}} c$ is the jet speed, $\rho_{\text{jet}}$ and $\beta_{\text{jet}}$ are the comoving jet mass density (assumed to be dominated by “cold” protons) and magnetic field, and $\rho_{\text{cld}}$ is the mass density of the clouds, which fill a fraction $\varepsilon$ (usually 1) of the jet volume (the tenuous radio-emitting plasma is assumed to pervade the bulk of the jet volume). The relativistic gas pressure is assumed to make a negligible contribution to the total jet energy flux; the limits on the energy density of synchrotron-emitting electrons calculated in the next section confirm that this is a valid assumption. If, on the other hand, the clouds and the radio-emitting plasma (plus magnetic fields) are moving in a subrelativistic jet (i.e., with a velocity $v_{\text{jet}} = v_{\text{BAL}} \lesssim 0.2c$), then the total jet energy flux simplifies to

$$ \frac{L_{\text{jet}}}{r^2 \Omega} \approx \frac{1}{2} \langle \rho_{\text{jet}} \rangle v_{\text{jet}}^3 + \frac{B_{\text{jet}}^2}{8\pi} v_{\text{jet}}, $$

(2)

where $\langle \rho_{\text{jet}} \rangle \approx \rho_{\text{jet}} + \varepsilon \rho_{\text{cld}}$ is now the average comoving mass density of the jet.

3. OBSERVATIONAL CONSTRAINTS

3.1. Covering Factor

The widely adopted, standard model for BALQs is chiefly founded upon the observational study by Weymann et al. (1991), who found no statistically significant differences between the spectral properties of BALQs and non-BALQs in a subsample taken from the Large Bright Quasar Survey, thus indicating that BALQs do not form an intrinsically different class of objects from non-BALQs. When combined with the constraint from scattering models that the broad absorption line region (BALR) cannot completely occult the continuum source (Junkkarinen 1983; see also Hamann, Korista, & Morris 1993), this result led to the suggestion that all RQQs possess a BALR with a global covering factor that can be identified with the incidence rate of
BALQs amongst an optically selected sample, typically \( \sim 0.1 - 0.15 \) (although the “true” incidence rate could be as high as 30% if attenuation is taken into account; see, e.g., Schmidt & Hines 1999 and references therein). It was then further suggested that a physically plausible distribution for absorbing cloudlets would be a quasi-equatorial geometry, possibly skimming the edge of an obscuring torus, which would provide a natural source of material for the cloudlets.

Note that a weak jet model may not necessarily be compatible with this covering factor interpretation of the BAL incidence rate amongst optically bright quasars. A poorly collimated jet could, in principle, freely expand to fill the biconical regions interior to the dusty torus, so that the half-opening angle of the “jet” could be as wide as 60°. Since optically bright quasars are also those seen along a direct line of sight to the continuum source (i.e., within these “ionization cones”), then the low incidence rate of BALs amongst these quasars may not necessarily be consistent with the jet covering factor; it then becomes necessary to consider the BAL phenomenon as an evolutionary, mass-loss phase (see, e.g., Miller 1997). Note that the original Weymann et al. (1991) results do not rule out a duty cycle effect for the BAL phenomenon (Weymann 1997), and indeed, there is some observational evidence to support the idea (see, e.g., Briggs, Turnshek, & Wolfe 1984; Boronson, Pearson & Oke 1985; Voit, Weymann, & Korista 1993) that BALQs may be transition objects between RQ and RL quasar phases that have undergone a close interaction and/or merger event which has triggered the expulsion of excess mass and angular momentum. One particularly impressive example is the recent adaptive optics image of the BALQ PG 1700 + 518 \((z = 0.29)\), which clearly reveals a discrete companion galaxy that appears to be merging with the quasar (Stockton, Canalizo, & Close 1998). Similarly, other BALQs which are sufficiently nearby \((z < 0.5)\) to show clear signs of having undergone a recent interaction or merger event include Q0025 + 024, IRAS 0759 + 6508, Q1402 + 436 and Q2141 + 175, and while several more show less discernible signs (e.g., PG 0026 + 129, PG 0043 + 039, Q0318 – 196, PG 1426 + 015, PG 2233 + 143), their immediate environs are strongly suggestive of interactions taking place. Finally, tidal tails and nearby companions associated with some low-z quasars have been detected by *Hubble Space Telescope* imaging (see, e.g., Bahcall et al. 1997), which has also revealed that the host galaxies of at least some bright RQQs, like those of RLQs and radio galaxies, are massive elliptical galaxies, which are believed to have been formed from mergers (McLure et al. 1998).

### 3.2. Orientation and Geometry

The strongest evidence for a quasi-equatorial geometry for the BALR has come from polarization measurements, which have revealed that, on average, BALQs tend to have higher levels of optical polarization than non-BALQs and which, when interpreted in terms of orientation alone, suggest that the BALR is being intercepted along highly inclined lines of sight (Hutsemékers, Lamy, & Remy 1998; Schmidt & Hines 1999 and references therein). These data have also revealed that the highest levels of polarization \((> 1\%)\) are measured in low-ionization BALQs (lo-BALQs; those with absorption lines due to low-ionization species, such as Mg ii and Al iii, in addition to the usual high-ionization BAL troughs). Since the objects in this subclass of BALQs also show evidence of strong dust reddening (Sprayberry & Foltz 1992), the polarization data strongly favor models in which the viewing angle is close to the obscuring dust torus. However, this is strictly only the case for lo-BALQs; polarization studies have found no statistically significant differences in the optical polarization between high-ionization BALQs (hi-BALQs) and non-BALQs (Hutsemékers et al. 1998), and therefore they offer no helpful clues to the orientation of hi-BALQs, which in fact make up the majority of BALQs.

Another way of determining the orientation and geometry of the BALR is to search for radio axes. Unfortunately, the large distances and low radio fluxes of RQQs have made it difficult in practice to resolve radio images of BALQs. Indeed, prior to the recent FIRST survey, only two BALQs had been mapped with sufficient spatial resolution with the VLA: PG 1700 + 518, which exhibits double compact radio structure down to 0′15 at 15 GHz (Hutchings, Neff, & Gower 1992; Kellermann et al. 1994; Kukula et al. 1998); and the Cloverleaf, H1413 + 1143, which exhibits compact radio counterparts to all four of the optical images produced by gravitational lensing, as well as an additional, strongly amplified radio source that appears to be associated with the quasar itself (possibly an ejected radio component; Kayser et al. 1990). Similarly, the newly discovered BALQ APM 0827 + 5255 (Irwin et al. 1998) exhibits double compact radio structure down to 0′28 at 3.5 cm (G. F. Lewis 1998, private communication). Even the recent FIRST survey—which has detected and mapped, with follow-up, high-resolution (A array) VLA imaging, about 20 BALQs—has failed to detect any elongated or extended structure that could be identified as radio axes; all of the sources appear pointlike down to a 0′.2 resolution level (B. Becker 1998, private communication). Although it may be possible to interpret these radio sources as weak, unresolved jets, it would be desirable to obtain higher quality radio data.

In the meantime, it is interesting to make a comparison with the low-luminosity, low-velocity counterparts to BALs found in Seyfert 1 galaxies which are sufficiently nearby to resolve linear radio structures on subkiloparsec and sometimes parsec scales. For example, NGC 3516, NGC 4151, and NGC 5548, which are classified as Seyfert 1.5 galaxies, all exhibit elongated radio structure with subcomponents...
and with an unresolved core centered on the optical nucleus (see, e.g., Baum et al. 1993). On the other hand, in other nearby AGN which exhibit BAL-like features (e.g., NGC 3783, NGC 509, NGC 7469), no radio axes are detected, only nuclear point sources. This is typically the case for objects which are classified as Seyfert 1.0–1.2 galaxies and which are therefore believed to be viewed at low inclinations, so it is unclear whether they actually possess linear radio structure that cannot be seen because of a lack of projection, or whether their radio sources are intrinsically different from those in other Seyfert galaxies, which seems less likely to be the case.

There are also other observational clues to suggest that not all BALQs are being viewed at large inclination angles. For example, dust models for the optical to submillimeter spectral energy distributions of H1413+117 and of APM 08279+5255 (both of which are IRAS sources) are consistent with a dusty torus being viewed face-on, with a direct, unobscured line of sight to the optical continuum source (Barvainis et al. 1993; Lewis et al. 1998). Similarly, the lack of reddening in other high-BALQs (see, e.g., Weymann et al. 1991) suggests that they too are being viewed at latitudes sufficiently high to avoid dust contamination from the putative torus. Furthermore, the remarkable similarity between the emission-line equivalent widths of BALQs and putative torus. Furthermore, the remarkable similarity between the emission-line equivalent widths of BALQs and putative tori which are classed as Seyfert 1.0–1.2 galaxies and with an unresolved core centered on the optical nucleus is expected to produce measurable differences if they are sufficiently high to avoid dust contamination from the putative torus. Furthermore, the remarkable similarity between the emission-line equivalent widths of BALQs and putative tori which are classed as Seyfert 1.0–1.2 galaxies and with an unresolved core centered on the optical nucleus.

The standard synchrotron formulae for a homogeneous source region can be used to place some limits on the physical properties of the radio-emitting plasma and magnetic fields that are capable of producing the observed radio flux densities of BALQs, which are typically approximately a few mJy. The emitting electrons are assumed to have the usual nonthermal energy distribution: \( n_e \propto \gamma^{-p} \), with a total electron number density \( n_e = \int \gamma d\gamma n_\gamma \), where \( \gamma \) is the electron Lorentz factor, with \( \gamma_{_{\text{min}}} \leq \gamma \leq \gamma_{_{\text{max}}} \), and where \( p \) is the particle spectral index. For optically thin synchrotron emission, the spectral index is given by \( \alpha = (p - 1)/2 \) and the observed flux density can be related to the other observable parameters, the angular diameter of the source, \( \theta_e \), and the luminosity distance, \( D \), according to (see Marscher 1987)

\[
S_\nu \approx (3 \times 10^4)\left(\frac{\gamma_e^2 B^2}{c^2}\right)\frac{n_e}{\min} \left(\frac{v_{\nu}}{\text{GHz}}\right) \frac{D_{\text{Gpc}}}{h} (1 + z)^{1/2} \text{mJy},
\]

where \( B \) is the magnetic field and \( \alpha = 1.0 \) has been used, since this is a typical value obtained from observed BALQ radio spectra for which spectral indices could be measured (Barvainis & Lonsdale 1997). To take into account the possibility that the observed radio flux has been boosted as a result of beaming (i.e., in RLQs), this expression needs to be further multiplied by a factor \( \delta^2 \), where \( \delta = [\Gamma(1 - \beta \cos \varphi)]^{-1} \) is the Doppler factor corresponding to a bulk velocity \( \beta c \) with a bulk Lorentz factor \( \Gamma \) and with a direction \( \varphi \) with respect to the observer.

To obtain independent constraints on the unknown source parameters \( n_e \) and \( B \), the optically thin synchrotron spectrum can be extrapolated down to the frequency \( \nu_m \) where the observed flux density reaches a maximum at a value \( S_m \) and where it can be assumed that the optical depth to synchrotron self-absorption is approximately unity (see Marscher 1987). This then gives the following relations:

\[
B \approx 40 \left(\frac{\nu_m}{\text{GHz}}\right)^5 \left(\frac{S_m}{\text{mJy}}\right)^{-2} \theta_e^2 (1 + z)^{-1} \delta G \text{ cm}^{-3},
\]

which is virtually independent of \( \alpha \), and for \( \alpha = 1.0 \):

\[
n_e \approx (4 \times 10^{-7}) \nu_m^2 \left(\frac{\nu_{\text{GHz}}}{\text{GHz}}\right)^{11} D_{\text{Gpc}}^{-1} (1 + z)^{1/2} \delta^{-6} \text{ ergs cm}^{-3},
\]

Although these relations are strongly dependent on the observable parameters, they can be somewhat useful when comparing the extremely contrasting properties between the compact radio cores of RLQs and the much weaker radio sources in RQQs (including BALQs). In particular, these relations imply a distinct difference between the ratio of energy densities in magnetic field, \( u_B \), to relativistic electrons, \( u_e \), for quasars with contrasting radio properties. Equation (4) implies a magnetic energy density \( u_B = B^2/8\pi \sim 50 v_{\text{GHz}}^{10} S_m^{11} \theta_e^2 (1 + z)^{-1} \delta^2 \text{ ergs cm}^{-3} \), while equation (5) implies an electron energy density (for \( \alpha = 1.0 \)) \( u_e = 2 \gamma_{_{\text{min}}}^2 n_e m_e c^2 \sim 10^{-12} v_{\text{GHz}}^{-9} S_m^{11} \theta_e^{-11} D_{\text{Gpc}}^{-1} (1 + z)^{1/2} \delta^{-3} \text{ ergs cm}^{-3} \). Interestingly, the ratio \( u_B/u_e \) for RQQs is larger by many orders of magnitude than the same ratio for RLQs (assuming the same observing frequency and the same redshift), even if a conservative flux density (say, 100 mJy) and a high Doppler factor (\( \delta \approx 10 \)) are used for the RL source. Also, the condition \( u_B/u_e \gg 1 \) is always obtained for BALQs, even in the case of the highest flux density level.
measured so far (for FIRST 1556 + 3517; one of the RL BALQ candidates), 30 mJy at 1.4 GHz, with \( z = 1.48 \) (Brotherton et al. 1998), which gives a lower limit of \( u_B/u_e \geq 0.1(v_{1.4} \theta_{\text{max}})^{1.9} D_{\text{Gpc}} \) and which, taking into account the strong dependence on \( \theta_{\text{max}} \geq 1 \), always exceeds unity by an appreciable amount.

The ratio \( u_B/u_e \) may have important implications for the nature of the radio-emitting source regions in quasars, especially in the framework of jet models. Falcke & Biermann (1995), for instance, suggest that there exists a "family" of jet models, the members of which are distinguished by differences in the equipartition conditions involving the energy densities in the magnetic field, relativistic electrons and protons as well as thermal electrons and protons and also differences in the total energy budget of the jet-disk system as a whole. According to their hypothesis, jets with \( u_B \gg u_e \) are predicted to be radio quiet if the relativistic electron distribution begins at \( \gamma_{\text{min}} \approx 1 \) and if \( u_B \) is below its equipartition value with respect to the bulk kinetic energy. They also further argue that jets with \( u_B \gg u_e \) and \( \gamma_{\text{min}} \approx 1 \) can be radio weak (but not radio quiet) if \( u_B \) is in equipartition with the bulk kinetic energy, thus offering a plausible theoretical discrimination between RQ and RI sources. Note that while the idea (see, e.g., Falcke et al. 1996) that RIQs are Doppler-boosted RQQs may seem appealing in the framework of a weak jet model, there is very little observational evidence for beaming in non-RLQs.

4. THEORETICAL CONSTRAINTS

Although various pressure-driven wind models have been proposed for BALs (see de Kool 1997 for a summary), the only direct observational clues to the nature of the driving force are line-locking features (Turnshek 1988) and "ghost of Lyα" features (Arav & Begelman 1994). There are, however, theoretical arguments to suggest that while line radiation pressure clearly plays an important dynamical role in the BAL phenomenon, it may not necessarily be the only acceleration mechanism. For instance, absorbing clouds will experience large forces when they move relative to an accelerating, confining medium, and thus they will be unavoidably dragged along by the dynamic pressure of the external fluid (Weymann et al. 1985). Indeed, Arav, Li, & Begelman (1994) have shown that BAL clouds comoving with the ambient medium produce profiles that more closely resemble those observed than do the profiles produced by line acceleration alone when the clouds are decoupled from the ambient medium. They also find that to produce a significant contribution to the overall acceleration from line pressure relative to ram pressure when the clouds are comoving, the starting radius is too close to the inferred radius of the broad emission line region, i.e., \( \sim 0.1 \) pc.

Another related problem is the cloud confinement mechanism. The temperatures required for pressure confinement by a thermal wind (see, e.g., Stocke et al. 1992) are difficult to achieve on \( \sim \) parsec scales, while a wind driven by cosmic rays (see, e.g., Begelman, de Kool, & Sikora 1991) also cannot provide the necessary pressure for confinement of BAL clouds. The confinement problem disappears if, instead of clouds, the BALs are produced by a quasi-continuous, high column density wind (see, e.g., Murray et al. 1995). Although such a model is made more appealing by being able to account for the common UV/X-ray (BALs/warm absorber) absorption features that have been detected in some sources (Crenshaw et al. 1999; Gallagher et al. 1999 and references therein), it requires ionization parameters several orders of magnitude in excess of the values inferred from the range of ionization states in the observed BAL troughs, and this also makes it difficult to account for local BALs.

Whether BAL clouds can be accelerated and confined by a weak jet and whether the physical properties of such clouds are consistent with those deduced from observations now remains to be determined.

4.1. Dynamical Considerations

Consider a blob of gas immersed in an outflowing medium. This blob, irrespective of its formation history, will quickly come into pressure equilibrium with its surroundings, and in doing so will be accelerated by the dynamic pressure of the outflow, expanding as it moves downstream. For a jet of speed \( \Gamma v_{\text{jet}} c \), the ram pressure exerted on a cloud of scale length \( r_{\text{cld}} \) satisfies

\[
\rho_{\text{cld}} v_{\text{cld}}^2 \frac{\partial v_{\text{cld}}}{\partial r} = \rho_{\text{jet}} \Gamma^2 (\beta_{\text{jet}} c - v_{\text{cld}})^2 \frac{v_{\text{jet}}}{r_{\text{cld}}} \tag{6}
\]

where \( v_{\text{cld}} \) is the cloud velocity. However, the momentum flux, \( \rho_{\text{jet}} \Gamma^2 \beta_{\text{jet}}^2 c^2 \), of a subrelativistic jet is higher than that of a relativistic jet with the same energy flux, i.e., the ratio of momentum-to-energy flux, \( (\Gamma/\Gamma - 1)\beta_{\text{jet}}/c \), is higher by a factor \( 2c/v_{\text{jet}} \), and therefore the dynamic pressure of a subrelativistic jet (of speed \( v_{\text{jet}} \)) provides a more efficient acceleration mechanism than that of a relativistic jet. Indeed, ram pressure acceleration in a relativistic jet is no more efficient than acceleration by line radiation pressure (the favored mechanism for BALs) for the same power in kinetic energy flux and photon flux. In a subrelativistic jet, on the other hand, the ratio of \( a_{\text{ram}} \) to \( a_{\text{rad}} \) is \( \sim c/v_{\text{jet}} \).

The higher efficiency of ram pressure acceleration in a subrelativistic jet compared with that in a relativistic jet led Blandford & Königl (1979) to predict that dense blobs embedded in a subrelativistic jet would naturally give rise to absorption troughs blueshifted with respect to their corre-
sponding emission lines. This also immediately suggests that a jet model offers a natural explanation for why nuclear absorption outflows, when present in RLQs, are never as strong as those which characterize bona fide BALQs.

4.1.1. The \( v_{\infty} - \)Radio-Loudness Anticorrelation

The distinct anticorrelation between the observed terminal velocity, \( v_{\infty} \), of material ejected from a quasar nucleus and the radio power of the quasar, as pointed out by Weymann (1997) following the FIRST discovery of BALs in RLQs (Brotherton et al. 1998), is clearly a key observational property which therefore provides a critical test for the dynamical aspects of any theoretical model. It is clearly difficult to interpret this observation in the context of models in which the momentum of the outflowing gas entirely derives from the radiation field. On the other hand, an outflow driven at least partially by the momentum flux of a radio-emitting jet, whose radio flux is some fraction of the total energy flux, clearly warrants a more quantitative investigation.

Consider a total column density \( N_{\text{cld}} \) of absorbing clouds accelerated along a line of sight by the dynamic pressure of a jet. These clouds will attain a terminal velocity according to (cf. eq. [6])

\[
\frac{v_{\infty}^2}{c^2} \lesssim \frac{\Gamma \beta_{\text{jet}}}{\Gamma - 1} \frac{2L_{\text{jet}}}{r_0 \Omega N_{\text{cld}} m_p c^3}, \tag{7}
\]

where \( r_0 = r_{0,\text{pc}} \) pc is the radius at which the acceleration commences and where equation (1) has been used. Thus, a subrelativistic jet can accelerate a total column density of \( 10^{22} N_{22} \) \( \text{cm}^{-2} \) clouds to comoving velocities

\[
v_{\infty} \lesssim 0.1c L_{46}^{1/2}(r_{0,\text{pc}} N_{22})^{-1/3} \left( \frac{\Omega}{4\pi} \right)^{-1/3}, \tag{8}
\]

which is consistent with the maximum velocities measured directly from the blueshifted absorption troughs in BALQs (see, e.g., Weymann et al. 1991). In the case of a mildly relativistic jet, with, say \( v_{\text{jet}} = 0.5c \) (corresponding to \( \Gamma = 1.15 \)), equation (7) implies a terminal velocity much less than the bulk jet speed, with

\[
v_{\infty} \lesssim 0.07c L_{46}^{1/2}(r_{0,\text{pc}} N_{22} v_{\text{jet},0.5})^{-1/3} \left( \frac{\Omega}{4\pi} \right)^{-1/2}. \tag{9}
\]

Note that in the limit of relativistic jet speeds (\( \Gamma \gtrsim \) a few), any dense clouds embedded in the flow will always be accelerated to the bulk velocity, unless the jet is “free,” with an opening angle \( \phi \gg \Gamma^{-1} \) (Begelman et al. 1984), in which case equation (7) implies \( v_{\infty} \lesssim 0.1c L_{46}^{1/2} \Gamma_3 (r_{0,\text{pc}} N_{22})^{-1/2} \). Thus, a jet model offers a viable explanation for why the outflow velocities associated with the much narrower, blue-shifted absorption lines in RLQs are never as high as the velocities associated with genuine BALs in RQQs.

It is also of interest to perform these calculations with lower energy fluxes to test the applicability of a weak jet model to the UV absorption features detected in some Seyfert galaxies (see, e.g., Crenshaw et al. 1999). Using appropriate scaled-down values for \( L_{\text{jet}} \) and \( r_0 \) of, say, \( 10^{43} \) ergs \( s^{-1} \) and 0.1 pc, respectively, equation (8) implies comoving velocities \( \lesssim 0.02c L_{46}^{1/3}(r_{0,0.1\text{pc}} N_{22})^{-1/3} (\Omega/4\pi)^{-1/3} \). This is consistent with observations, which indicate that the absorption features in Seyfert spectra are never as broad as those seen in their more luminous counterparts, with terminal velocities of \( \lesssim 0.015c \) typically being measured, compared with \( \lesssim 0.2c \) for the BALQs.

Thus, a jet model for BALQs can not only explain the observed \( v_{\infty} - \)radio-loudness anticorrelation in quasars, but can also explain the lower \( v_{\infty} \) values measured from weaker absorption features in less powerful sources.

4.1.2. Kelvin-Helmholtz Instability

Small-scale clouds moving with a relative velocity with respect to the bulk velocity of the surrounding plasma are susceptible to the Kelvin-Helmholtz instability, which can shred the clouds into smaller and smaller entities. For clouds embedded in a magnetized medium, moving with a relative velocity \( \Delta v \), the fastest growth timescale corresponding to the most disruptive modes is (see, e.g., Celotti et al. 1998; see also Begelman et al. 1991)

\[
t_{\text{KH}} \simeq \frac{r_{\text{cld}}}{\Delta v} \left( \frac{\rho_{\text{cld}}}{\rho_{\text{jet}}} \right)^{1/2}. \tag{10}
\]

\( t_{\text{KH}} \) is the sound-crossing timescale across the clouds, corresponding to an internal sound speed \( c_s = (2kT_{\text{cld}}/m_p)^{1/2} \). In other words, the instability is sufficiently rapid to restrict the confinement of clouds to timescales as short as \( t_{\text{sc}} \). Since the acceleration timescale is much longer than \( t_{\text{KH}} \), this means that clouds must be continuously regenerated or injected along the outflow.

In the nonlinear regime, the Kelvin-Helmholtz instability causes a rapid cascade of cloud fragmentation. While this does not directly destroy the clouds, it makes them increasingly more prone to microphysical diffusion processes, which can assimilate the clouds into the ambient medium, thereby effectively causing their evaporation. This is examined in § 4.2.2 below (see also Weymann et al. 1985 for a discussion).
4.2. Physical Constraints

In the following, it is assumed that the BAL cloudlets are comoving with the bulk flow of a subrelativistic jet, since the arguments presented in § 4.1.1 indicate that this may be an appropriate model for bona fide BALQs. From equation (2), the total power in a subrelativistic jet can be written as

\[ L_{\text{jet}} \gtrsim r^2 \Omega_{\text{jet}}^2 \frac{<\rho_{\text{jett}}> v_{\text{jett}}^3}{m_p}, \tag{11} \]

from which an upper limit on the mean jet density can be obtained:

\[ <\rho_{\text{jett}}>/m_p \lesssim (4 \times 10^{-3}) L_{\text{jet},46} r_{\text{pc}}^{-2} \left( \frac{v_{\text{jett}}}{0.1c} \right)^{-3} \left( \frac{\Omega}{4\pi} \right)^{-1} \text{ cm}^{-3}. \tag{12} \]

4.2.1. Confinement

A crucial issue which needs to be addressed by any physical model for BALQs is the confinement mechanism. If BAL clouds are accelerated by the dynamic pressure of a weak jet, then ram pressure provides a natural confinement mechanism. This corresponds to the equipartition condition \( \rho_{\text{cld}} v^2_s \approx \rho_{\text{jett}} v_{\text{jett}}^2 \). Using equation (11), this implies a characteristic cloud density

\[ n_{\text{cld}} \lesssim \frac{2L_{\text{jet}}}{r^2 \Omega_{\text{jet}} kT_{\text{cld}}} \approx 10^{10} L_{\text{jet},46} r_{\text{pc}}^{-2} \left( \frac{v_{\text{jett}}}{0.1c} \right)^{-1} \]

\[ \times \left( \frac{\Omega}{4\pi} \right)^{-1} \left( \frac{T_{\text{cld}}}{3 \times 10^4 \text{ K}} \right)^{-1} \text{ cm}^{-3}, \tag{13} \]

which is consistent with the upper limits deduced from the observed ionization species and from photoionization models (see e.g., Turnshek 1988).

It is also possible that comoving magnetic fields provide pressure support to dense cloudlets. The typical field strength of a comoving magnetic field is

\[ B_{\text{jet}} \approx L_{\text{jet},46} r_{\text{pc}}^{-1} \left( \frac{v_{\text{jett}}}{0.1c} \right)^{-1/2} \left( \frac{\Omega}{4\pi} \right)^{-1/2} \text{ G}, \tag{14} \]

which satisfies the equipartition condition \( B_{\text{jet}}^2 / 8 \pi \approx n_{\text{cld}} kT_{\text{cld}} \approx n_{\text{cld}} kT_{\text{cld}} / r^2 \Omega_{\text{jet}} \approx 5 \rho_{\text{jett}} v_{\text{jett}}^2 \). According to Falcke & Biermann (1995), jets in which the magnetic field is below equipartition with the bulk kinetic energy are likely to be radio-quiet sources, so this could be a distinguishing property between bona fide BALQs and the RL BALQ candidates. Although magnetic fields need not play an important dynamical role in a weak jet model for BAL outflows, even small field strengths can be of crucial importance to maintaining a two-phase fluid by suppressing transverse diffusion of relativistic particles (whose motion is confined to a Larmor radius about the field lines) into cool, dense BAL clouds. However, longitudinal diffusion can still be important and therefore needs to be examined.

4.2.2. Evaporation

A serious threat to the survival of BAL clouds embedded in a jet is evaporation into the ambient plasma as a result of diffusion and Coulomb heating by the external fast particles which fill the bulk of the jet. The volume heating rate due to Coulomb collisions between thermal, nonrelativistic \((kT_e \ll m_e c^2)\) electrons and nonthermal, relativistic electrons is given by (see, e.g., Gould 1972; see also Jackson 1975)

\[ H_{\text{Coul}} \approx \frac{3}{2} \chi_{e} n_{\text{cld}} n_{e} \sigma_{T} m_e c^3 \mathcal{A}(\gamma), \tag{15} \]

where \( \chi_{e} \) is the ratio of the number density of thermal electrons (either free or harmonically bound to ions) in the cloud gas to the total cloud density and \( \mathcal{A}(\gamma) \) is a parameter which only weakly depends on \( \gamma \) and which is related to the logarithmic Gaunt factor, determined from the maximum and minimum impact parameters. For collisions with free electrons, which determine the overall heating of the cloud gas, \( \mathcal{A}(\gamma) \approx \ln (\sqrt{\gamma - 1} m_e c^2/\hbar \omega_p) \), where \( \omega_p \) is the (thermal) electron plasma frequency. Equation (15) corresponds to a collision timescale

\[ t_{\text{coll}} \approx \frac{2\gamma}{3n_{\text{cld}} \sigma_{T} c \mathcal{A}} < 10^{5} n_{\text{cld},8}^{-1} \frac{\gamma}{\mathcal{A}} \text{ s}, \tag{16} \]

where \( n_{\text{cld},8} = n_{\text{cld}}/10^{8} \text{ cm}^{-3} \). This must be appreciably longer than the sound-crossing timescale, \( t_{\text{sc}} \), if pressure confinement of individual clouds is to be sustained in spite of the collisions, implying cloud sizes

\[ r_{\text{cld}} \approx (5 \times 10^{11}) n_{\text{cld},8}^{-1} \left( \frac{T_{\text{cld}}}{3 \times 10^4 \text{ K}} \right)^{1/2} \frac{\gamma}{\mathcal{A}} \text{ cm}. \tag{17} \]

This is smaller than the mean free path between the collisions, \( \lambda_{\text{mfp}} = t_{\text{coll}} \beta c \) (where \( \beta c \) is the velocity of the relativistic electrons) by a factor \( \sim c/c_s \sim 10^4 \), which means that the relativistic electrons would have to travel through as many clouds before a Coulomb encounter occurs and diffusive effects become important. In other words, the particle energy in the ambient jet plasma is simply advected through the clouds, rather than transferred diffusively, as a result of direct encounters between the thermal and nonthermal elec-
trons. Furthermore, this will only strictly be true if the magnetic field lines in the jet penetrate the clouds with little distortion. If the clouds possess a random, internal field line structure (which they might do if they were preexisting entities that were swept up by the jet rather than being formed from condensations within the jet), then the tangential component of the internal field lines can prevent the infiltration of fast particles from outside the clouds.

It has been pointed out, however, that collective plasma effects, triggered by the passage of fast particles through a "cold" plasma, can enhance the heating rate, equation (15), by a factor as large as $10^5$ (see Ferland & Mushotzky 1984 and references therein). If this is the case, then the only way cool clouds can maintain their properties in the presence of fast particles is to efficiently radiate away any extra energy input. The dominant radiative cooling process in a typical BAL cloud is through the C IV $\lambda 1549$ line transition, which has an Einstein coefficient $A_{21} \approx (2.6 \times 10^3) \text{ cm}^{-3} \text{s}^{-1}$. The volume cooling rate for this line transition is then $n_{\text{CIV}} A_{21} \lambda 1549 \approx (3 \times 10^{-4}) \xi_{\text{CIV}} n_{\text{cld}}$ ergs $\text{cm}^{-3}$, where $\xi_{\text{CIV}} = n_{\text{CIV}} / n_{\text{cld}}$ is the abundance of the C IV ion relative to the total (ionized plus neutral) hydrogen density in the clouds. The total heating can be quantitatively estimated as $\approx \zeta H^\text{Coul}$, where $\zeta \approx 10^5$ takes into account collective plasma heating and where $H^\text{Coul}$ is integrated over the nonthermal electron distribution (neglecting the weak $\gamma$-dependence in the $B$ parameter). The ratio of the cooling to heating rates is then

$$\frac{C^\text{CIV}}{H^\text{tot}} \approx 10^6 n_{\text{jet}}^{-1} \xi_5^{-1} \left( \frac{\xi_{\text{CIV}}}{10^{-4}} \right) \text{cm}^{-3},$$

where $\xi_5 = \xi / 10^5$ and where an appropriate value of $B = 25$ has been used. Thus, radiative line cooling in the clouds is efficient enough to overcome any extra heat input from the ambient relativistic jet plasma provided its density is $n_{\text{jet}} \ll 10^6 \text{ cm}^{-3}$. According to the limits on $n_{\text{jet}}$ imposed by the total jet energy budget, equation (12), this is always satisfied and therefore evaporation does not pose an immediate threat to the survival of BAL clouds embedded within a weak, subrelativistic jet.

### 5. SUMMARY AND DISCUSSION

It has been argued that the phenomenon of nuclear absorption outflows from quasars provides an important clue to understanding the observed radio-loud/radio-quiet dichotomy in active galactic nuclei if interpreted in terms of an inhomogeneous weak jet model in which the thermal gas responsible for the observed UV absorption troughs is embedded within a poorly collimated outflow of weakly radio-emitting plasma. The motivation for this model is threefold: (i) observations of radio-quiet quasars have confirmed that the nature of their radio emission is fundamentally similar to that of radio-loud quasars; (ii) the observed anticorrelation between the terminal velocity of outflowing thermal gas and the radio strength of the quasar is direct evidence that the dynamics of the thermal, absorbing gas is intimately linked to the properties of the nonthermal, radio-emitting plasma; and (iii) lower velocity intrinsic absorption outflows have also been detected in Seyfert galaxies, many of which are found to exhibit linear radio structure indicative of small-scale, weak jets.

The observational constraints obtained here corroborate other theoretical jet models which attribute the differences in radio strength (i.e., quiet, weak, and loud) to differences in the physical properties of jets (e.g., total energy flux, bulk speed, relative quantities of thermal and nonthermal plasma). It has also been suggested that a weak jet interpretation of the observed radio flux may offer a viable explanation for why nuclear absorption outflows are not detected in strong radio sources; the relativistic jets which power these sources are thought to be propitious sites for in situ particle acceleration, which precludes the accumulation of cooled particles that can thermalize and condense to form localized gas clouds capable of producing absorption features. Furthermore, since the efficiency of ram pressure acceleration increases as a jet becomes subrelativistic, the observed anticorrelation between the terminal velocity of the outflowing thermal gas and the radio strength of the quasar can also be explained by a weak jet model. Finally, it has been demonstrated that this model can explain the narrow UV absorption features detected in some Seyfert 1 galaxies. Thus, it has been shown that a weak jet model is successful in explaining not only the high-velocity outflows in bona fide broad absorption line quasars, but also the lower velocity nuclear absorption outflows detected in both their strong radio counterparts and low-luminosity counterparts.

The importance of broad absorption line quasars to our understanding of the radio-loud/radio-quiet dichotomy becomes evident in the framework of a weak jet model, of which the underpinning implication is that all AGN possess radio-emitting jets to varying degrees and that their observational classification depends not only upon orientation, but also upon the intrinsic differences in the physical properties of their jets. However, one key issue which is yet to be fully resolved is the role evolutionary effects play in the formation of jets and outflows in AGN; if mass ejection phenomena are evolutionary phases, then the true significance of broad absorption line quasars in the grand scheme of AGN unification is yet to be fully appreciated.

The author wishes to thank the Royal Commission for the Exhibition of 1851 Research Fellowship (Imperial College, London) for financial support and A. C. Gower and G. F. Lewis for helpful discussions.

1999 PASP, 111:954–963
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