Draft version June 9, 2008
Preprint typeset using LaTeX style emulateapj v. 10/09/06

STELLAR DISRUPTION BY SUPERMASSIVE BLACK HOLES AND THE QUASAR RADIO LOUDNESS DICHOTOMY

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Draft version June 9, 2008

ABSTRACT

The origin of the dichotomy of radio loudness among quasars can be explained using recent findings that the mass of the central supermassive black hole (SMBH) in extended radio-loud quasars is systematically a few times that of their counterparts in radio-quiet quasars. This sensitive dependence of radio jet ejection upon SMBH mass probably arises from the blockage of jets by the presence of substantial quantities of gas tidally stripped from stars by the central BH. This disruptive gas, however, will only be available around BHs with masses less than $M_c \gtrsim 10^8 M_\odot$, for which the tidal disruption radius lies outside the SMBH's event horizon. Consequently, we find that AGN with $M_{BH} > M_c$ can successfully launch jets with a wide range of powers, thus producing radio-loud quasars. The great majority of jets launched by less massive BHs, however, will be truncated in the vicinity of the SMBH due to mass loading from this stellar debris. This scenario also can naturally explain the remarkable dearth of extended radio structures in quasars showing broad absorption line spectra.

Subject headings: black holes — galaxies: active — galaxies: jets — quasars: absorption lines — quasars: general — radio: continuum

1. INTRODUCTION

The bi-modality in the distribution of the radio-to-optical flux ratio, R, was first revealed using optically selected samples (e.g., Kellermann et al. 1989). A similar picture emerged from the plot of radio flux versus [O III] line intensity for QSOs (the latter marks the accretion power of the central engine), which showed that radio loud quasars (RLQs) are typically $\sim 10^4$ times more radio luminous than radio quiet quasars (RQQs) at a given $L_{[OIII]}$ (e.g., Miller, Rawlings & Saunders 1990; Xu et al. 1999). However, a somewhat ambiguous view of this dichotomy emerged from more recent investigations based on deep, large sky area radio surveys (FIRST, Becker et al. 1995; NVSS, Condon et al. 1998) and extensive optical surveys (SDSS, York et al. 2000; 2dF, Croom et al. 2001). Thus, while a radio loud fraction of $5-10\%$ was estimated in some studies (e.g., Ivezić et al. 2002, 2004), other papers reported no radio-loudness bimodality (White et al. 2000; Cirasuolo et al. 2003). Laor (2003) has argued that these negative results are probably an artifact of the lower sensitivity of the FIRST radio survey to extended radio emission, which, unlike the core emission, is unbeamed, and hence a more reliable indicator of the jet power. In fact, a double peaked distribution of R, is seen in an "image stacking" analysis of the FIRST data for QSOs (White et al. 2007).

It is unlikely that the host galaxy morphology or the large-scale environment play a crucial role in the radio loudness dichotomy since in both these respects, optically bright RQQs are very similar to RLQs (Metcalf & Magliocchetti 2006, hereafter MM, and references therein). Therefore, it has been suggested that the main difference between RLQs and RQQs lies in the availability of SMBH spin energy to power the jets in RLQs (e.g., Wilson & Colbert 1995; Hughes & Blandford 2003). In the scheme of Sikora, Stawarz & Lasota (2007), radio powerful jets, driven by the SMBH spin, are realized intermittently whenever a strong collimation is externally imposed on them by the MHD wind from the accretion disk (see, also, Nipoti et al., 2005).

A key observational clue for the radio dichotomy may stem from the inferred mass-related duality of radio loudness, in that powerful radio sources are only associated with galactic nuclei containing central black holes of masses $M_{BH} > 10^8 M_\odot$ (Laor 2003; Dunlop et al. 2003; Chiaberge, Capetti & Macchetto 2005; Sikora et al. 2007). Note that this clue does not exclude the spin of the black hole or accretion disk from being the basic mechanism underlying jet formation. However, for radio detection the jet must be able to emerge from the nuclear region out to parsec scale. An "aborted" jet scenario recently invoked by Ghisellini, Haardt & Matt (2004) envisions that radio-quiet AGN too eject relativistic particle jets but they are terminated due to the impact of infalling shells of "heavy" material that are ejected by the AGN intermittently. A likely case of an intermittently aborted jet comes from the X-ray monitoring of the RQQ PG 1407+265 (Gallo 2006) which is believed to possess a highly Doppler boosted compact radio jet (Blundell et al. 2003).

While nuclear jet abortion may offer an attractive route to explaining radio quietness, can it be reconciled with the *dichotomy* of radio loudness of quasars, which itself appears to be sensitively linked to M_{BH}? Specifically, it needs to be understood how the jet abortion scenario ties in with the observed systematic mass difference between the central SMBHs of RLQs and RQQs and the finding that all RLQs have $M_{BH} > 10^8 M_\odot$ (Laor 2003; see above). Several recent studies using different techniques and based on large-sky radio and optical surveys have revealed a consistent mass excess of

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the central black-holes powering RLQs vis-a-vis those in RQQs (Dunlop et al. 2003; MM; Jarvis & McLure 2006; Hyvönen et al. 2007). The determinations of M_{BH} in these studies are based both on optical spectroscopy of the nuclei and accurate photometry of host galaxies using the Hubble Space Telescope. Moreover, care was taken that the samples of RQQs and RLQs are matched in redshift and optical luminosity. Thus, even though it is only by a modest factor (1.4 to 4), the presence of a mass excess of the BHs in RLQs over those in RQQs has been found in independent studies. Clearly, if this is the main factor behind the radio dichotomy, the underlying physical process must be very sensitive to M_{BH}. A possible link of the SMBH critical mass, (M_c), to the radio dichotomy, via tidal disruptions of stars, was noted in Laor (2000) but discounted on the ground that any influence of the tidal debris would be too short lived as the debris would be quickly sucked into the SMBH on a dynamical time scale (sub-day). Below we argue that even the modest difference found between the BH masses in RLQs and RQQs could play a critical role in aborting the nascent jets in RQQs.

2. DISRUPTED STARS CAN CHOKE NASCENT JETS

In our picture, twin-jets of relativistic plasma are driven by the SMBH spin (e.g. Blandford & Znajek 1977) or by the accretion disk (e.g., Blandford & Payne 1982), and/or by variants involving a magnetic coupling between the BH and accretion disk (e.g., Wilms et al. 2001). Still, it is clear that the success of these powerful jets in making the extended radio lobes typical of RLQs depends critically on the resistance the fledging jets encounter in crossing the SMBH environment.

A jet with kinetic power L_j and Lorentz factor Γ will carry a mass flux

$$\dot{M}_j = L_j/\Gamma c^2. \qquad (1)$$

If a mass flux exceeding $\dot{M}_j$ intercepts the jet with a large covering factor, the jet will be drastically slowed down and effectively quenched (e.g., Hubbard & Blackman 2006). We investigate if a plausible source of thermal plasma needed for mass loading the nascent jet is the wide-spread debris resulting from tidal disruption of stars in the vicinity of the SMBH. This nuclear tidal debris (NTD), although first invoked to fuel quasars (e.g., Hills 1975), has been normally deemed rather inadequate (e.g., Frank & Rees 1976). However, NTD accretion is often invoked to explain the X-ray or UV flares occurring in the nuclei of some non-active galaxies (Rees 1988; Gezari et al. 2006). As argued by Rees (1988) and Ayal et al. (2000), part of the tidal debris would accrete on to the SMBH, either in Bondi mode, or through a disk (e.g., Hills 1978). There are two important time scales: the average time interval, t_i, between the close approaches of the stars to the SMBH, and the viscous time scale of accretion through a disk or torus, t_v. Rescaling the results of Evans & Kochanek (1989) who carried out numerical studies of stellar disruption for $M_{BH} = 10^6 M_\odot$, to the $10^8 M_\odot$ mass range, we estimate that for a star of energy E, the orbital time, roughly $\propto \sqrt{M_{BH}^2/(-E)^3}$ is $\sim 10^3$ times longer (i.e., hours). The tidal interaction energy, being $\propto M_{BH}^{2/3}$, implies more energetic disruptions of stars around the most massive BHs. The viscous time is higher than the orbital time by a factor, $\mathcal{M}^2/\alpha = 10^7$, where the Mach number $\mathcal{M} = v_\phi/c_s$. This would yield a torus or disk life time of about 10^3 yrs. Since we expect $t_i \simeq 100$ yrs (see below), $t_i \lesssim t_v$. This result, along with independent orbital planes of successively captured stars, would result in a long lasting, quasi-spherical distribution of debris planes, and thus a Bondi type infall of the stripped gas would ensue. Since the inspiral time due to gravitational radiation losses ($\propto M_{BH}^{8/3}$) is orders of magnitude longer for the most massive SMBHs, the above scenario is strengthened. But, to be on the conservative side, this additional input to accretion rate, and hence perhaps to the jet power, will be ignored here.

A crucial point for this scenario is that most estimates place the central BH of powerful quasars (RLQs and RQQs) in the mass range $\sim 10^8 - 10^9 M_\odot$ (§1). At these masses, even a factor of two decrease in M_{BH} could have drastic consequences for NTD creation, rendering a jet's emergence critically dependent on M_{BH}. For $M_{BH} = M_c \approx 3 \times 10^8 M_\odot$ the Schwarzschild radius, r_s, becomes equal to the tidal radius, r_T, at which solar type stars would be shredded upon passage close to the BH (Hills 1975). Due to relativistic effects, and depending on the BH spin, M_c can be reduced to become close to $1 \times 10^8 M_\odot$ (Hills 1978; Rees 1988). Then even if the pericenter of a star, r_{min}, becomes smaller than r_T ($< r_s$) it will create little debris via tidal disruption, as it is swallowed whole by the SMBH. For slightly less close flybys (r_{min} = 2–3 r_T) only the outer layers of the star are disrupted. Therefore, for $M_{BH} > M_c$, most main sequence stars and all compact remnants would be swallowed whole by the central SMBH and the only contributors left to generate debris around the SMBH are giant stars (Hills 1978; Frank 1978). Although rare within the cores of early-type galaxies, giants could be responsible for the jet abortions needed to explain the association of a few RQQs with extremely massive black holes ($\sim 3 \times 10^8 M_\odot$; e.g., MM). Thus, in our scenario, when $M_{BH} \to 3 \times 10^8 M_\odot$, the disappearance of the captured typical (sun-like) stars into the BH event horizon, without producing jet disrupting NTD, can immensely boost the prospects of the jet's escaping from its origin to form an RLQ. For the majority of stars the differences in the value of M_c that arise from variations in the stars' binding energies, will be slight ($M_c \propto \bar{\rho}_*^{-1/2}$) so that a systematic excess of SMBH mass for RLQs should be maintained.

Stellar dynamical models require that a certain fraction of stars in the central region of an active galaxy will pass within r_T of the central SMBH (e.g., Frank & Rees 1976; Rees 1988). A good approximation to the rate at which mass is shred in the vicinity of the BH by tidal disruption of stars is given by (Frank 1978; Rees 1988)

$$\dot{M}_D = 4.6 \times 10^{-2} M_8^{4/3} n_{c,5} \sigma_2^{-1} (r_{min}/r_T), \qquad (2)$$

where M_8 is the mass of the SMBH in units of $10^8 M_\odot$, $n_{c,5}$ is the density of typical (main sequence) stars in the galactic core in units of $10^5 \mathrm{pc}^{-3}$, σ_2 is the core's stellar velocity dispersion in units of 100 km s^{-1}, and r_{min} is the minimum distance of approach to the SMBH. As the BH provides a sink, the stellar distribution cannot be isothermal, but follows a power-law cusp in stellar density (Peebles 1972; Bahcall & Wolf 1976). Taking into account the depletion of stars in low angular momentum (loss cone) orbits and replenishment by diffusion, Frank & Rees (1976) found that the resulting mass loss rate retains the form of Eq. (2), and is close to estimates made by Hills (1975). Recent numerical studies (e.g., Magorrian & Tremaine 1999; Wang & Merritt 2004) seem to indicate $10-100$ times lower feeding rates. Although the classical loss cone theory which was developed for the BH in centers of globular clusters is not valid for young galactic nuclei (i.e., lower mass unrelaxed systems, treated by Wang & Merritt 2004 and Magorrian & Tremaine 1999; see above), it is quite relevant for systems with masses ($\gtrsim 10^8 M_\odot$) which are of interest here; see Merritt (2006). However, all disruption rate predictions are beset with considerable uncertainties, summarized by Merritt (2006): the classical loss cone theory depends critically on the stellar density profiles, the system's relaxation state, how the distribution function depends on angular momentum and the stellar contribution to the gravitational potential. All these can significantly change the outcome. In particular, in collisionless young galactic nuclei, feeding rates can be much higher than in a relaxed nucleus if the nucleus is triaxial and many of the orbits are "centrophilic" (Merritt 2006).

Direct observations, on the other hand, can only provide a lower limit to $\dot{M}_D$, and the feeding rates can be an order-of-magnitude higher than the 10^{-3}M$_\odot$ yr^{-1} estimated by Donely et al. (2002). For example, Ivanov et al. (2005) argue that the observed flaring rate weakly constrains the disruption rate to be of order 10 times the nominal rate. In view of these uncertainties, we adopt here the analytical estimate given by Eq. (2).

It is expected that about half of the tidal debris will be expelled in a fast moving spray of gas at a characteristic velocity $\sim 10^4 M_6^{1/6}$ km s^{-1} (Rees 1988). We propose that this expelled debris forms the broad absorption line clouds (§3), whereas the debris bound to the BH would eventually fall back to $r \sim r_T$ and then it could be partly ejected in a sustained wind driven by the quasar radiation. A substantial fraction, η, of $\dot{M}_D$ will, however, be NTD spread in streams or clumps throughout a parsec-scale region around the SMBH, albeit concentrated in the inner few r_T.

The jet should have a fairly large solid angle, $\Omega_j \sim 0.3-1.0$ sr on sub-parsec scale, as revealed by VLBI for M87 (Biretta, Junor & Livio 2002) and Cen A (Horiuchi et al. 2006). The tidally stripped gas may eventually fall in nearly isotropically or it may be funneled through a bicone of solid angle Ω_D somewhat less that 2π sr aligned with the SMBH spin axis. Thus, the condition for jet disruption due to mass loading by the NTD becomes

$$\eta \dot{M}_D \Omega_j / \dot{M}_j \Omega_D > 1. \quad (3)$$

Substituting from Eqns (1) and (2) for $\dot{M}_j$ and $\dot{M}_D$,

$$M_8^{4/3} n_{c,5} \sigma_{c,2}^{-1} \eta f_{0.1} L_{44}^{-1} \Gamma_{10} > 0.038, \quad (4)$$

where we have conservatively taken $r_{min} = r_T$, and normalized to typical values $f_{0.1} = 10\Omega_j/\Omega_D$, $\Gamma_{10} = \Gamma/10$ and $L_{44} = L_j/10^{44}$erg s^{-1}, corresponding to a moderately powerful jet. In Fig. 1 we show the regimes in which a jet of kinetic power L_j is likely to be aborted by the NTD via mass loading, for various combinations of n_c ($10^4 - 10^8$ pc^{-3}) and Γ (1–100). Estimated values for

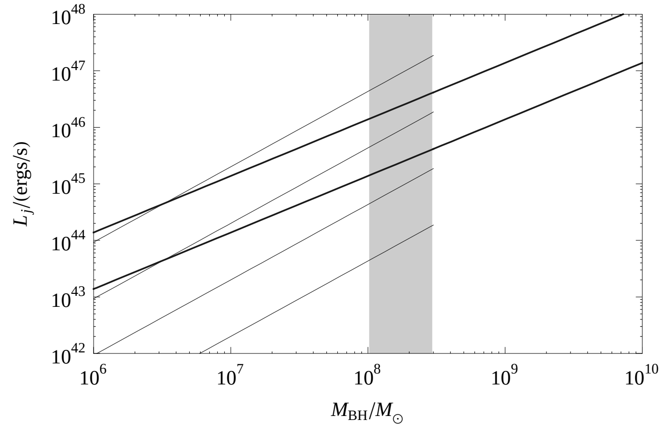

Fig. 1.— Allowed ranges for L_j against M_{BH}. The two thick lines denote L_{Edd} (top) and $0.1 L_{Edd}$ (bottom) upper limits to the jet KINETIC luminosity. The vertical band indicates the range of M_c. The thin lines show the minimum L_j needed for successful ejection beyond pc-scales for (top to bottom): $n_c\Gamma = 10^8, 10^7, 10^6, 10^5$ pc^{-3}.

$n_c \sim 10^7$ pc^{-3} are indicated in several observations and the stellar cores have a typical radius of order of 10 pc (based on HST imaging by Capetti & Balmaverde 2005); however we normalize conservatively for a fiducial value of 10^5 pc^{-3}. Further, we take $\sigma_c = 300$ km s^{-1}, $\eta = 0.5$ and $f = 0.1$ as typical values, as they vary less than the other parameters. Fig. 1 also shows two nominal upper limits to jet's kinetic power based on the SMBH Eddington luminosity: 0.1 L_{Edd}, which is probably realistic; and a strong upper limit of 1.0 L_{Edd}.

For $M_{BH} > M_c = 1 - 3 \times 10^8M_\odot$, jets of any power can escape as the tidal debris is largely absent. But even in this regime, if $n_c > 10^8$ pc^{-3}, stellar collisions will release debris (e.g., Frank 1978), but this contribution is unlikely to be relevant unless $M_8 \gg 1$. On the other hand, for $M_{BH} < M_c$, Fig. 1 places significant lower limits to the powers of jets which can successfully pierce the NTD cloud. For AGN with such central SMBH and relatively large n_c only jets of sufficiently low Γ can escape disruption by NTD. At the same time, since the maximum jet power attainable is expected to be some fraction (~ 0.1) of L_{Edd}, the range of kinetic power of successful jets is constricted.

Thus, in our model, there are two regimes that allow escape of low power jets from the nuclear region: 1) a relatively low mass central BH, as found in Seyfert galaxies ($M_8 \sim 0.03-0.3$), launching rather slow jets through stellar cores of relatively low density; 2) an extremely massive BH ($M > M_c$), as in RLQs (§1). The ability of even weak jets to be successfully launched by such massive BHs accords with the finding that RLQs of very similar M_{BH} can span an enormous range in radio luminosity (e.g. MM). This also explains why even weak AGN, such as LINERS, are able to eject (low power) jets if they are hosted by massive ellipticals with $M_{BH} > M_c$ (Chiaberge et al. 2005; Maoz 2007).

The recent study by White et al. (2007) applied an image stacking technique to the FIRST survey to obtain a sample of over 41,000 SDSS quasars. They find that the radio luminosity rises roughly as the 0.85 power of the optical luminosity, implying that the radio loudness factor R slowly declines with optical power. This result concurs with our picture, in that the optically most luminous objects, expected to host the most massive BHs, can have a wide range of (unbeamed) radio powers, whereas the lower mass objects only have jet powers in a narrow range with the minimum set by tidal debris and the maximum imposed by the Eddington limit (Fig. 1).

3. ADDITIONAL OBSERVATIONAL IMPLICATIONS

We now briefly discuss some other observational results that fit nicely within our picture.

Although broad absorption line (BAL) gas has now been detected in $> 25\%$ of quasars (e.g., Trump et al. 2006), its dearth among the powerful, edge-brightened (FR II) radio sources seems striking (Gregg, Becker & de Vries 2006). However, this anti-correlation is absent at 10–100 μJy flux levels where BAL quasars are, in fact, found to be radio brighter than their non-BAL counterparts (White et al. 2007). Attributing the difference to Doppler boosting, White et al. have suggested that the the jets in BALQSOs are even better aligned to our direction than the jets of the majority of the QSOs, which would imply that the BAL clouds are also present in the polar direction. They interpret this in terms of an evolutionary unification model (Lípari & Terlevich 2006) where during a specific phase, low-level radio emission still confined near the central engine is accompanied by an abundance of absorbing clouds that are quickly eliminated as the radio jet breaks out to form a genuine RLQ.

Alternatively, in our picture, the jet's breaking out, and the consequent formation of a powerful radio source, is usually only possible if there is a dearth of NTD. Should the debris be created via stellar disruption (for $M_{BH} < M_c$), not only would it cause jet abortion though mass loading but also an appreciable fraction of the gaseous debris would be expelled at $\gtrsim 10^4$ km s^{-1}(Rees 1988). In our model these gaseous clumps are observed as the BAL clouds, ionized in the intense radiation field of the accretion disk and its corona. This is also consistent with the observed high abundance of Fe II in BALQSOs (e.g., Yuan & Wills 2003).

Further, active galaxies with luminous extended emission line regions (EELRs), on a 10 – 100 kpc scale, have recently been found to have lower (sub-solar) metallicities in their broad line regions (BLRs), as compared to the super-solar metallicities typically found in the BLRs of weak EELR galaxies (Fu & Stockton 2007a). Since EELRs are thought to be blown out by jets (e.g. de Breuck et al. 2000; Fu & Stockton 2007b) their presence requires, in our scenario, a dearth of tidal debris. The lack of high metallicity BLR clouds can thus indeed be expected to correlate with jet-induced EELR prominence.

Lastly, while mergers of two SMBHs are expected to yield core type ellipticals (cf. Capetti & Balmaverde 2006), they are unlikely to cause the observed high incidence of radio-loudness in such ellipticals via spinning up the SMBHs. Following a merger of identical SMBHs with randomly oriented spins, a simple vector addition averaged over all directions of aligned angular momenta and magnetic field, B, results in a reduction of the spin energy loss rate by a factor of 12 since it is $\propto a^2B^2M_{BH}^2$ (here B is normalized for flux conservation and a for mass conservation). Taking radiation of angular momenta and relativistic effects into account, this rate can drop even further (Hughes & Blandford 2003). A plausible alternative follows from the result that SMBHs in core type ellipticals are typically a few times more massive than those found in power-law ellipticals (Capetti & Balmaverde 2006). It is this factor (leading to more cases of $M_{BH} > M_c$) that is likely to explain the strong link of radio-loudness to core type ellipticals. The crucial role of M_{BH} is evident from Fig. 7 of Capetti & Balmaverde (2006) where all quasars with $M_{BH} > 3 \times 10^8 M_\odot$ are found to be radio loud (see, also, Laor 2000).

To summarize, compared to their RQQ counterparts, the observed systematic excess of the masses of the central BHs in RLQs could account for the radio dichotomy, despite the mass excess being just by about a factor of two. This is because even this marginally larger mass can ensure that the tidal disruption radii for most (i.e., main sequence) stars fall within the event horizons of the SMBHs for most RLQs. Therefore, only in these more massive central engines will the tidal debris material not be available for mass loading the nascent jets, allowing them to emerge. In contrast, the majority of jets launched from less massive BHs will encounter widespread tidal debris and will probably be disrupted on the sub-parsec scale, thus appearing as radio-quiet AGN. Since part of the tidal debris is expected to be expelled at high velocities ($\sim 10^4$ km s^{-1}), it could give rise to the metal-rich BAL features. This way, the marked lack of BALs in extended radio quasars also can be easily understood.

We thank the referee for insightful comments. PJWs work is supported in part by a GSU subcontract to NSF grant AST05-07529 at the University of Washington.

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