

ON THE ORIGIN OF RADIO CORE EMISSION IN RADIO-QUIET QUASARS

KATHERINE M. BLUNDELL

Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK; k.blundell@physics.ox.ac.uk

AND

ZDENKA KUNCIC

School of Physics, University of Sydney, Physics Road, Sydney, NSW 2006, Australia; z.kuncic@physics.usyd.edu.au

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ABSTRACT

We present a model for the radio emission from radio-quiet quasar nuclei. We show that a thermal origin for the high brightness temperature, flat spectrum point sources (known as radio “cores”) is possible provided that the emitting region is hot and optically thin. We hence demonstrate that optically thin bremsstrahlung from a slow, dense disk wind can make a significant contribution to the observed levels of radio core emission. This is a much more satisfactory explanation, particularly for sources where there is no evidence of a jet, than a sequence of self-absorbed synchrotron components that collectively conspire to give a flat spectrum. Furthermore, such core phenomena are already observed directly via milliarcsecond radio imaging of the Galactic microquasar SS 433 and the active galaxy NGC 1068. We contend that radio-emitting disk winds must be operating at some level in radio-loud quasars and radio galaxies as well (although in these cases, observations of the radio cores are frequently contaminated/dominated by synchrotron emission from jet knots). This interpretation of radio core emission mandates mass accretion rates that are substantially higher than Eddington. Moreover, acknowledgment of this mass-loss mechanism as an AGN feedback process has important implications for the input of energy and hot gas into the intergalactic medium (IGM) since it is considerably *less directional* than that from jets.

Subject headings: accretion, accretion disks — quasars: general

1. INTRODUCTION

Radio-quiet quasars are strongly accreting yet lack the extensive 100 kpc scale jets that steadily transport away energy and angular momentum from the nuclei of radio-loud quasars and radio galaxies. The weak radio core emission associated with radio-quiet quasars has been revealed by a succession of very long baseline interferometry (VLBI) observations usually to be compact on milliarcsecond (\sim parsec) size scales (Blundell et al. 1996; Falcke et al. 1996; Blundell & Beasley 1998; Ulvestad et al. 2005). The luminosities of the cores in such objects can be as high as VLBI measurements of cores in many radio-loud quasars (10^{21} – 10^{24} W Hz $^{-1}$ sr $^{-1}$) when imaged with resolution of a few milliarcseconds; comparable brightness temperatures (10^6 – 10^9 K) are revealed by these observations as well. The physical size scales of the observed cores reported in these papers for radio-loud and radio-quiet quasars have a robust upper limit of a few cubic parsecs even at redshift $z \sim 1$.

Observations of some nearby Seyfert nuclei reveal a flat-spectrum component on milliarcsecond scales with a misalignment of up to 90° from the linear radio structure on arc-second scales (e.g., Middelberg et al. 2004). In some cases, a nonthermal origin for radio cores is directly ruled out by observations: VLBI observations of the nucleus in NGC 1068 in particular reveal linear parsec-scale radio structure perpendicular to the radio jet axis (Gallimore et al. 1997), with a brightness temperature, $T_b \approx 10^6$ K, too low to be consistent with synchrotron self-absorption (SSA; Gallimore et al. 1996). Its radio spectrum measured between 5 and 8.4 GHz is $\propto \nu^{0.3}$. Gallimore et al. (2004) suggest that the observed radio properties of the NGC 1068 nucleus are best explained in terms of free-free emission from a disk wind.

The purpose of this Letter is to construct a model for AGN cores based on this and on observations of the resolved disk-wind outflow from the nuclear regions of the Galactic microquasar SS 433, which arises from optically thin bremsstrahlung

(Blundell et al. 2001), as an alternative to the long-standing model of a sequence of synchrotron self-absorbed components that conspire to give a smooth flat spectrum (Cotton et al. 1980).

1.1. Beyond Cosmic Conspiracy Theory

The interpretation of the “cosmic conspiracy” core model—that is, a sequence of distinct homogeneous components each having a peaked spectrum that together give rise to the integrated smooth flat spectrum core as in the case of the BL Lacertae object 0735+178 (Cotton et al. 1980)—has been applied to many observations of cores in the last three decades. In many subsequent observations of many different objects there has been no direct observational evidence supporting this paradigm and indirect evidence against it, even under the scrutiny of sub-milliarcsecond, multi-epoch observations (e.g., Rantakyro et al. 1998; Gómez et al. 2000; Jorstad et al. 2005; Ly et al. 2007). There is simply no evidence in support of multiple self-absorbed components that conveniently have successively higher turnover frequencies to explain the overall integrated spectral properties of stationary cores. We are compelled, therefore, to explore the validity of an alternative model in which the mechanism responsible for the radio emission is optically thin bremsstrahlung arising from a disk wind, rather than embryonic, and moving, jet knots.

2. DISK WINDS AS A SOURCE OF FLAT SPECTRUM RADIO CORE EMISSION?

A common misconception is that high observed brightness temperatures necessarily imply a nonthermal source. While it is true that a high brightness temperature T_b rules out optically thick thermal emission (because T_b cannot exceed the gas temperature, T_g , which is low in the case of an optically thick source because a blackbody is an efficient radiator), optically *thin* thermal emission cannot be ruled out as readily. The brightness

temperature of an optically thin thermal source of size R is $T_b \approx c^2 j_\nu R / (2k\nu^2)$, where j_ν is the volume emissivity at frequency ν . At temperatures above $T_e \approx 10^7$ K, gas is completely ionized, and if the plasma is sufficiently dense and remains subrelativistic, then two-body (i.e., free-free) processes dominate Compton processes. The brightness temperature can then be expressed as $T_b \approx \tau_\nu^{\text{ff}} T_e$, where $\tau_\nu^{\text{ff}} \lesssim 1$ is the free-free optical depth. Thus, a high brightness temperature can arise from a thermal plasma provided that it is hot and marginally optically thin. Moreover, because the spectral index of bremsstrahlung emission is $\alpha \approx -(h\nu/kT_e) \log e$ (where $\alpha \equiv d \log S_\nu / d \log \nu$ and S_ν is the flux density at frequency ν), a flat spectrum is naturally produced at radio frequencies ($h\nu \ll kT_e$).

In the following, we consider a thermal accretion disk wind that is present at radii $r \geq r_w$, where r_w is the disk radius at which the wind is launched (see Begelman et al. 1983; King & Pounds 2003). Within this radius, outflows are likely to become Poynting-flux-dominated and form a magnetized corona and/or jet. Self-absorbed synchrotron radiation from the jet can of course contribute to the unresolved core radio emission. We consider the possibility that the thermal disk wind also contributes to flat-spectrum core radio emission through optically thin free-free radiation. At the base of the wind, the electron number density, N_e , can be related to the mass outflow rate, \dot{M}_w , via the continuity equation

$$N_e(r_w) \approx \frac{\dot{M}_w}{4\pi f_\Omega r_w^2 \mu m_p v_w}, \quad (1)$$

where v_w is the escape speed at this radius and $f_\Omega = \Omega/4\pi \ll 1$ is the geometrical covering factor of the outflow. This gives

$$N_e \approx 1 \times 10^{12} f_{\Omega,0.1}^{-1} \frac{\dot{M}_w}{M_\odot \text{ yr}^{-1}} \left(\frac{r_w}{10^{15} \text{ cm}} \right)^{-2} \times \left(\frac{v_w}{500 \text{ km s}^{-1}} \right)^{-1} \text{ cm}^{-3}, \quad (2)$$

where $f_{\Omega,0.1} = f_\Omega/0.1$ and where we have used a mean molecular weight $\mu = 0.5$ for fully ionized hydrogen. At these densities, the base of the wind is highly opaque (see King & Pounds 2003). We now consider the properties of the wind farther out.

Optically thin thermal emission from the disk wind can become important beyond a photospheric radius r_{ph} where the wind becomes transparent. This is the radius at which the effective optical depth, $\tau_{\text{eff}} = [\tau_{\text{ff}}(\tau_{\text{ff}} + \tau_{\text{es}})]^{1/2}$ (Rybicki & Lightman 1979), is unity as viewed by a distant observer. Here τ_{ff} is the optical depth due to free-free absorption and τ_{es} is the electron scattering optical depth. To determine r_{ph} from the condition $\tau_{\text{eff}} \approx 1$, we first calculate separately the scattering and absorption photospheric radii r_{es} and r_{ff} and determine the physical conditions under which they are approximately equal. Using $N_e \propto r^{-2}$ from mass continuity (eq. [1]), the radius r_{es} at which $\tau_{\text{es}} \approx 1$ is determined from $\int_{r_{\text{es}}}^\infty \sigma_T N_e dr \approx 1$, where σ_T is the Thomson scattering cross section. This gives

$$r_{\text{es}} \approx \frac{\sigma_T \dot{M}_w}{4\pi f_\Omega \mu m_p v_w} \approx 8 \times 10^{17} f_{\Omega,0.1}^{-1} \frac{\dot{M}_w}{M_\odot \text{ yr}^{-1}} \left(\frac{v_w}{500 \text{ km s}^{-1}} \right)^{-1} \text{ cm}. \quad (3)$$

Similarly, the radius r_{ff} at which $\tau_{\text{ff}} \approx 1$ is determined from $\int_{r_{\text{ff}}}^\infty \kappa_\nu^{\text{ff}} dr \approx 1$, where $\kappa_\nu^{\text{ff}} \approx 0.018 \bar{g}_{\text{ff}} \nu^{-2} T_e^{-3/2} N_e^2 \text{ cm}^{-1}$ is the free-free absorption coefficient and \bar{g}_{ff} is the velocity-averaged free-free Gaunt factor (Rybicki & Lightman 1979). This gives

$$r_{\text{ff}} \approx 0.39 \bar{g}_{10}^{-1/3} \nu^{-2/3} T_e^{-1/2} \left(\frac{\dot{M}_w}{4\pi f_\Omega \mu m_p v_w} \right)^{2/3} \text{ cm}, \\ \approx 8 \times 10^{17} \bar{g}_{10}^{-1/3} \nu_{8 \text{ GHz}}^{-2/3} T_7^{-1/2} f_{\Omega,0.1}^{-2/3} \times \left(\frac{\dot{M}_w}{M_\odot \text{ yr}^{-1}} \right)^{2/3} \left(\frac{v_w}{500 \text{ km s}^{-1}} \right)^{-2/3} \text{ cm}, \quad (4)$$

where $\nu_{8 \text{ GHz}} = \nu/8 \text{ GHz}$, $T_7 = T_e/10^7 \text{ K}$, and $\bar{g}_{10} = \bar{g}_{\text{ff}}/10$. Thus, a hot disk wind that is optically thin to both electron scattering and radio-frequency free-free absorption can exist beyond a photospheric radius $r_{\text{ph}} \approx 0.1\text{--}1 \text{ pc}$.

We now consider the bremsstrahlung radio power emitted by the optically thin part of the wind. The specific bremsstrahlung luminosity is

$$L_\nu \approx 4\pi f_\Omega \int_{r_{\text{ph}}}^\infty j_\nu^{\text{ff}} r^2 dr, \quad (5)$$

where j_ν^{ff} is the free-free volume emissivity. For an electrically neutral hydrogen plasma, $j_\nu^{\text{ff}} \approx 6.8 \times 10^{-37} \bar{g}_{10} T_e^{-1/2} N_e^2 \exp(-h\nu/kT_e) \text{ ergs s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}$ (Rybicki & Lightman 1979). This gives a specific luminosity per solid angle

$$L_{\nu,\Omega} = \frac{L_\nu}{\Omega} \approx 2 \times 10^{-36} \bar{g}_{10} T_e^{-1/2} \times \left(\frac{\dot{M}_w}{4\pi f_\Omega \mu m_p v_w} \right)^2 r_{\text{ph}}^{-1} \text{ ergs s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \\ \approx 3 \times 10^{20} \bar{g}_{10} T_7^{-1/2} f_{\Omega,0.1}^{-2} \left(\frac{\dot{M}_w}{M_\odot \text{ yr}^{-1}} \right)^2 \times \left(\frac{v_w}{500 \text{ km s}^{-1}} \right)^{-2} \left(\frac{r_{\text{ph}}}{0.1 \text{ pc}} \right)^{-1} \text{ W Hz}^{-1} \text{ sr}^{-1}. \quad (6)$$

2.1. Observed Core Luminosities

White et al. (2007) applied an innovative technique to measure radio core emission from the quasars in the SDSS DR3 quasar catalog (Schneider et al. 2005). By stacking images from the FIRST survey (Becker et al. 1995), they found radio core luminosities in the range of $10^{21}\text{--}10^{24} \text{ W Hz}^{-1} \text{ sr}^{-1}$, consistent with luminosities measured on milliarcsecond scales (Blundell et al. 1996; Falcke et al. 1996; Blundell & Beasley 1998; Ulvestad et al. 2005). Of course, one cannot be sure that the core luminosities measured by White et al. (2007) are not elevated because of contamination by synchrotron emission from moving jet knots. Indeed, Blundell et al. (2003) have direct observational evidence for a highly relativistic jet in the bona fide radio-quiet quasar PG 1407+263.

3. SUPER-EDDINGTON ACCRETION?

A comparison of the radio wind luminosities predicted by equation (6) and observed radio core luminosities indicates that disk winds can make a nonnegligible contribution to observed radio core luminosities only if there is significant mass loss, with \dot{M}_w exceeding the Eddington limit, $\dot{M}_{\text{Edd}} \approx 3\eta_{0.1} M_8 M_\odot \text{ yr}^{-1}$, where $M = 10^8 M_8$ is the black hole mass and $\eta = 0.1\eta_{0.1}$ is the radiative efficiency. This in turn implies accretion rates $\dot{M}_a \gg \dot{M}_{\text{Edd}}$. The main role of the disk wind is then to remove excess angular momentum, thereby reducing the accretion rate at smaller radii (Königl & Pudritz 2000).

Are super-Eddington accretion and outflow rates plausible? We remark that the Eddington limit is based on simplifying (and incorrect) assumptions of spherical symmetry and a fiducial 10% radiative efficiency. The brightest radio galaxies and quasars have bolometric luminosities $L \approx 10^{46}\text{--}10^{47} \text{ ergs s}^{-1}$, requiring mass accretion rates of $\dot{M}_a \gtrsim 1\text{--}10 M_\odot \text{ yr}^{-1}$. This is a lower limit because the observed radiative output is almost certainly only a small fraction of the total power extracted from accretion, much of which can be converted into low radiative efficiency phenomena such as magnetized jets and/or a corona (see Kuncic & Bicknell 2004, 2007b).

Similarly, mass outflow rates for warm, dense ionized gas inferred from X-ray absorption spectra of quasars and Seyferts are typically $0.1\text{--}10 M_\odot \text{ yr}^{-1}$ (Chartas et al. 2002; Pounds et al. 2003a, 2003b; O’Brien et al. 2005; Pounds & Page 2006). Again, these values imply super-Eddington accretion. In the case of SS433, the mass outflow rate inferred for the observed radio wind is $\approx 4 \times 10^{-4} M_\odot \text{ yr}^{-1}$ (Blundell et al. 2001). If this Galactic microquasar is a $10 M_\odot$ black hole, then this implies an astonishing mass-loss rate of $\dot{M}_w \sim 10^3 \dot{M}_{\text{Edd}}$.

4. IMPLICATIONS

4.1. Correlated Radio and Optical/UV Emission

If radio core emission arises at least in part from an optically thin disk wind, then we may expect to observe a correlation between the radio wind emission and the optical/UV blackbody disk emission. This is expected because the disk wind can modify the local radial structure of the accretion flow, resulting in a disk emission spectrum that is redder and dimmer than that of a disk without outflows (Kuncic & Bicknell 2007a). Such a correlation has indeed been reported by White et al. (2007, their Fig. 14), who find that the SDSS DR3 quasars with redder colors tend to have higher mean radio flux densities and are radio-louder than quasars with standard colors.¹

In addition, White et al. (2007, their Fig. 9) find a remarkably tight correlation between the 5 GHz median radio luminosity and the absolute magnitude at 2500 Å rest-frame wavelength, with the specific radio and optical luminosities related via $L_R \sim L_{\text{opt}}^{0.85}$. The disk wind model predicts that $L_R \approx L_{\text{opt}}$ and that optical bremsstrahlung wind emission should begin to contribute significantly to the observed (K -corrected) mean optical quasar luminosity at 2500 Å (rest frame), $L_{\text{opt}} \approx 4 \times 10^{30} \text{ ergs s}^{-1} \text{ Hz}^{-1}$, when $\dot{M}_w \gtrsim 10 M_\odot \text{ yr}^{-1}$ (see eq. [6]). Thus, unless the mass-loss rate is extraordinarily high (that is, higher than the rates inferred from other independent observations; cf. § 3), it is likely that the optically thick disk emission, rather than the optically thin disk wind emission, is primarily responsible for the observed 2500 Å

emission. Remarkably, when White et al. (2007) calculate the radio loudness parameter, $R^* = L_R/L_{\text{opt}}$, adjusted to remove the strong radio/optical correlation, they find $\log R^* \sim 0$ (their Fig. 11). While it is not clear that this result is definitive, because of their assumption that all radio cores at all redshifts have a straight spectral index of $\alpha = -0.5$ (for which there are many counterexamples, some of them seemingly systematic with redshift), we note that our disk wind model provides a natural explanation for $\log R^*$ (corrected for blackbody disk emission) being consistently close to zero.

The parsec-scale cores of radio-quiet quasars are comparable in luminosity, size, and brightness temperature to those in radio-loud quasars. We suggest that the model explored in this Letter has applicability to the stationary, unresolved, flat spectrum components revealed by milliarcsecond VLBI observations, now an established technique for revealing moving and evolving synchrotron-emitting jet knots (e.g., Gómez et al. 2000; Jorstad et al. 2005; Ly et al. 2007), and even revealed with global VLBI techniques with tens of microarcsecond resolution (Rantakyro et al. 1998).

4.2. Duty Cycles of Quasars and Two Distinct Modes of Energy Feedback: Jets and Disk Winds

Blundell & Rawlings (1999, 2000) have presented evidence (from physical arguments and from the observed near-absence of any relic radio lobes) that lobe emission must disappear on relatively rapid timescales. From the similarity between the duty cycle of intermittent jet activity in microquasars (their flaring mode) and the fraction of quasars that are observed to be radio-loud, Nipoti et al. (2005) posit that radio-loudness is a function of the epoch at which a quasar is observed. The present Letter suggests that when there is no evidence for kiloparsec-scale jets or their lobes, which disappear rapidly following too much expansion, the observed persistence of weak unresolved radio cores is a strong indicator that mass loss via a disk wind accompanies ongoing disk accretion. Indeed, it seems increasingly likely that radio-loudness in quasars is a somewhat short-lived phase of enhanced angular momentum loss via jets, analogous to that in microquasars, and that the more common means of angular momentum loss is via longer lived phases of mass loss via disk winds. Separately from the flaring mode associated with jet-ejection episodes in microquasars, Nipoti et al. (2005) identify a second, chief mode of energy loss, which they term the “coupled mode” during which microquasars are observed to have closely coupled X-ray and radio luminosities and to be unresolved “cores.” If the quiescent radio core emission is due to a hot ($\sim 10^7$ K) disk wind, then the observed radio/X-ray correlation could be attributed to a common disk origin for the radio (disk wind) and soft X-ray (disk wind+disk blackbody) emission. It would be interesting to pursue this analogy further in the context of core emission in quasars and AGNs (although in this case, only the disk wind, and not the disk blackbody emission, would contribute to the soft X-ray emission) and indeed the extent to which the disk wind, if equatorial as in SS433, plays the role of the putative obscuring torus.

Although it is now widely acknowledged that feedback from AGNs is required to reconcile simulations of galaxy formation with observations, the details of these processes remain to be explored (e.g., Nesvadba et al. 2006). In particular, although jets are invoked as a means of relocating mass and energy away from the AGN, a limitation of this picture is that jets are by

¹ A positive correlation between radio loudness and bluer quasars is also evident in the catalog, although White et al. (2007) suggest this is most likely due to beamed synchrotron emission, i.e., jet contamination.

their very nature *highly directional* and relatively light. Winds from accretion disks, however, are considerably less directional and heavier and may provide a better means of dispersing mass/energy into the IGM and explaining the observed link between growth of supermassive black holes and their host galaxy properties (King 2005). A mass outflow rate ($\dot{M}_w \gtrsim \dot{M}_{\text{Edd}}$) of hot ($\sim 10^7$ K) gas may be sufficient to offset cooling in galaxies.

5. CONCLUDING REMARKS

We have proposed that the radio cores of radio-quiet quasars are thermal in origin, arising from an accretion disk wind. This wind naturally produces flat spectrum radio emission via optically thin bremsstrahlung radiation. The remarkable similarities in radio core properties of radio-quiet and (many) radio-loud quasars suggests that a radio-emitting disk wind is present

at some level in all quasars. The observed luminosities of radio core emission from quasars implies that they are accreting at super-Eddington rates and that the disk wind expels most of this matter well before it reaches the inner accretion flow, thereby providing an efficient mechanism for angular momentum transport and AGN feedback.

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