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Radio-loud and radio-quiet quasars: one population, different epochs of observation

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Abstract. I bring together evidence for the *rapidity* with which quasars' radio synchrotron lobe emission fades and for the *intermittency* with which jet plasma is ejected from individual quasars and radio galaxies and affirm the picture presented by Nipoti et al. (2005) that the radio-loudness of quasars is a function of the epoch at which they are observed. I briefly illustrate this account with examples of successive episodes of jet activity where the axis along which jet plasma is launched appears to have precessed. A new model for the weak core radio emission from radio-quiet quasars, that is not any kind of jet ejecta, is also briefly described.

1. How rapidly do radio lobes fade?

It is a remarkably powerful observation that the radio sky does not appear to be populated by vast numbers of dead or nearly dead radio sources. This is remarkable because radio galaxies and quasars are not thought to be older than a few, perhaps several, 10^8 years. Since the age of the Universe is now widely believed to be 13.7 billion years (Bennett et al. 2003), and given that radio galaxies and quasars are routinely discovered out to redshifts corresponding to lookback times of 12 billion years (e.g. Cruz et al. 2007), it would be reasonable to expect evidence of the cadavers of a good many radio galaxies and quasars. However, only a very few bona fide dead radio galaxies are known (e.g. Cordey 1987) although careful, deep studies are being rewarded with a few more examples (Parma et al. 2007).

1.1. Do we actually see a different picture at long radio wavelengths?

It is remarkably unusual that any radio galaxy or quasar has a different morphology at low frequency ($<$ 100s MHz) from its high frequency (GHz) morphology. It is worth noting that the challenges of using interferometers to image extended emission at GHz frequencies can disguise just how *unusual* is synchrotron plasma that emits only at very low frequencies and not at all at GHz frequencies. This hints that low-frequency synchrotron emission fades (nearly) as rapidly as high-frequency synchrotron emission and that synchrotron cooling is not the dominant energy-loss mechanism for the synchrotron plasma that radio lobes are composed of. In fact, evidence from matching the characteristics of complete samples of low-frequency selected classical double radio sources in luminosity (P), linear size (D), redshift (z) and spectral index (α) with those of simulated sources in these same characteristics led Blundell et al. (1999) to this realisation, which was investigated in more detail by Blundell & Rawlings (2000).

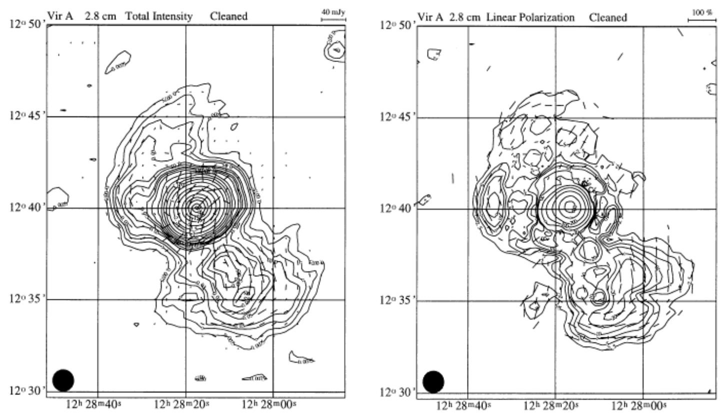

Figure 1. The halo of M87 at 10 GHz, whose imaging at this relatively high frequency by Rottmann et al. (1996), and also by Andernach et al. (1979), preceded the beautiful image at 330 MHz by Owen et al. (2000).

The lobes of synchrotron emitting plasma associated with powerful active galaxies such as classical double radio galaxies and quasars are observed to be as much as several hundred kiloparsec in extent. It was pointed out a number of decades ago (Jenkins & Scheuer 1976) that *if* synchrotron cooling played a part in determining the spectral shape of extended lobes, then the lobes should be more extended at lower frequencies. This rarely appears to be the case! For example, observations of some 3C radio galaxies at 151 MHz and 1.4 GHz (Leahy et al. 1989) show that the lobe lengths at these different frequencies are the same. Fig. 3 of Blundell et al. (2000a) shows that the images of 3C 219 at 74 MHz and at 1.5 GHz are more remarkable for their similarities than for their differences. Just as in the cases of 3C 98 and 3C 390.3 (Blundell et al. 2002) there is no evidence of any extended emission at low frequency which is not already seen at GHz frequencies; this appears to be the case for all the classical doubles imaged to date. If synchrotron cooling plays a very significant role in determining the spectral shapes of lobes, then we might expect to see *lobes that extend further at low frequency than at high frequency.* There is no evidence for e.g. backflow perpendicular to the source at 74 MHz which is not detected at GHz frequencies. Observations suggest that the Lorentz factor particles responsible for the 74 MHz emission are entirely co-spatial with those responsible for the 1.4 GHz emission. This is a first piece of evidence suggesting that synchrotron particles of all energies permeate the lobe magnetic field in the same way, despite the fact that the high-γ particles have shorter radiative lifetimes than the lower energy ones.

1.2. What do spectral index gradients really tell us?

A second piece of evidence that synchrotron particles of all energies permeate the lobe magnetic field in the same way may come from observations of the way that spectral indices change along these lobes (e.g. Winter et al. 1980;

Myers & Spangler 1985; Alexander & Leahy 1987): the general trend observed is that the lobe spectra are flatter in the outermost regions near the hotspot and steeper in the regions nearer the core. Often the observed change in spectral index with distance, or the spectral gradient, is steady and systematic.

The traditional interpretation of spectral gradients goes as follows: the radiating electrons nearer the core were dumped by the hotspot much earlier in the past than the radiating electrons near the hotspot now, and so the former will have undergone greater synchrotron cooling compared with the latter. A radiating population whose energy distribution is initially a power-law, which suffered only synchrotron losses, would result in a 'break' in this power-law. This break frequency moves to lower frequencies as more time elapses (Kardashev 1962; Pacholczyk 1970) predicting steeper measured spectral indices for the older emission near the centre of the source. The location of this break has been said to relate to the time elapsed since the radiating particles were accelerated, in the so-called *spectral ageing* method (Alexander & Leahy 1987; Myers & Spangler 1985), however, there are considerable problems with this paradigm which have been explored (Blundell & Rawlings 2000) and summarised (Blundell & Rawlings 2001) elsewhere. One such problem is the inconsistency of this interpretation with the observation that spectral gradients are observed well below the break frequencies in some lobes. For example, the images of Cygnus A between 74 MHz and 330 MHz (Kassim et al. 1996) shows a clear spectral gradient at frequencies well below the fitted break frequencies (Carilli et al 1991). This behaviour would not be observed if the spectral shapes at these frequencies were power-laws. This observation is more consistent with the assumption that there is a magnetic field gradient along the lobe which 'illuminates' different parts of a curved spectrum (in Lorentz factor γ) at a given observing frequency (Blundell & Rawlings 2001).

The fast transport model, however, can potentially explain the observations rather better: a gradient in magnetic field along the lobe together with the same curved energy electron spectrum throughout the lobe will result in a spectral gradient being observed at all frequencies. Indeed, analysis of multi-frequency images of Cygnus A (Rudnick et al. 1994) show no evidence for any variation of the curved $N(\gamma)$ spectrum across different regions of the lobe. Another remarkable result of this analysis is that the *bright* filaments in the lobes of Cygnus A have *flatter* spectra than the surrounding lobe material and also the same spectrum in Lorentz factor γ as elsewhere in the lobes, consistent with the idea that in high B-field regions such as filaments, the flatter part of the γ-spectrum is 'illuminated' while in the lower B-field regions higher-γ particles are obviously required to give the radiation at the particular $\nu_{\rm obs}$ and thus exhibit a steeper spectrum.

There is no trivial identity which connects the radiative lifetimes of the syncrotron-emiting particles with the age of the source, as described by Blundell & Rawlings (2000).

Consistent with the short radiative lifetimes of the synchrotron particles is the observation that there are hardly any known dead radio galaxies which have been observed. There are barely a handful of objects (such as Cordey (1987); Parma et al. (2007)) that have extended lobes while lacking any evidence for current on-going particle acceleration (e.g. in hotspots or cores) even in the low-frequency sky. This confirms the radiative lifetimes of synchrotron particles in the lobes being significantly shorter than the radiant lifetimes of the radio galaxies themselves.

1.3. How does synchrotron plasma age?

If it is true that for classical double (FRII) radio sources we see the same picture at long wavelengths (corresponding to $\sim 100\,\mathrm{MHz}$) as we do at GHz frequencies, then this is a further indication that energy losses of the synchrotron particles in the lobes are *energy-independent* (such as would arise from adiabatic losses) rather than *energy-dependent* (such as would arise from synchrotron or inverse Compton cooling).

It is important to realise that if the dominant energy losses are energy-independent then searches at long wavelengths will *not* reveal examples of relic activity in the Universe. It is only if the dominant loss mechanisms are energy-dependent that the low-frequency Universe will look significantly different from the GHz Universe we already know.

2. Evidence for intermittency in quasars and radio galaxies

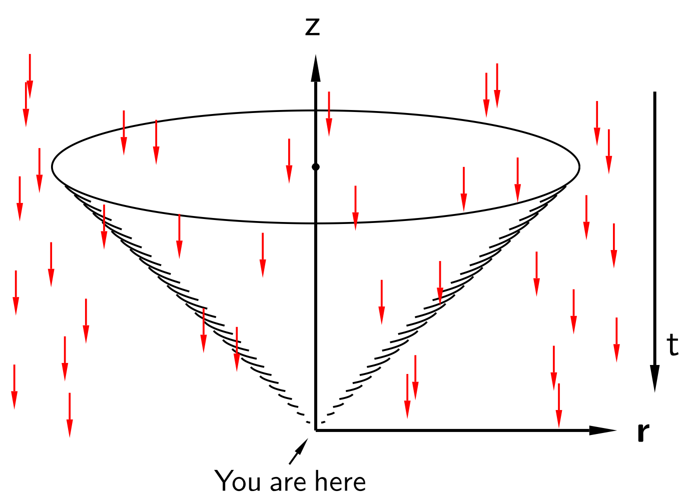

Figure 2. A schematic illustration of our light-cone. Each arrow represents the timeline of a radio source, whose lifetime is short compared to the Hubble time. Only those arrows which intercept our light-cone are those which we can observe. The point in a radio galaxy's lifetime when it is intercepted by our light-cone is of course random; thus, whether we see a quasar to be radio-loud or radio-quiet is random, with the relative numbers of radio-loud and radio-quiet quasars being determined by the duty-cycle of sustained jet ejection in quasars.

To glean evidence of intermittency in the jet activity of quasars is more challenging to obtain than evidence of intermittency in the jet activity of microquasars. This is of course because microquasars evolve on human-friendly timescales of hours, days and weeks whereas the analogous phenomena in quasars take $10^5 - 10^7$ years, vastly longer than human timescales.

What might be the manifestation of episodic jet activity in quasars? If the radio synchrotron plasma we observe from jets/lobes in quasars arises from relativistic particles with high Lorentz factors (e.g. 10^4 and above) then episodic jet activity would be evinced by the detection of relic examples of such plasma, characterized by lower Lorentz factors, nearer 10^3 for example. Particles with Lorentz factors of 10^3 are special because they inverse-Compton scatter photons that comprise the peak of the Cosmic Microwave Background (CMB) radiation to keV X-ray photons that are fairly easy to detect with Chandra and XMM. Searches for relic jet activity (manifested as dead radio lobes) revealed by X-ray observations for such upscattered emission have so far proved to be rather fruitful and are discussed below.

3. Episodic jet activity in quasars: "double-double" examples

A classical illustration of episodic activity in radio galaxies and quasars are the so-called "double-double" radio galaxies. There are beautiful studies of such examples by Schoenmakers et al. (2000), Saripalli et al. (2002), Saripalli et al. (2003), Saikia et al. (2006) and Jamrozy et al. (2007).

It seems that nature knows how to regenerate jet activity both along fairly similar jet axes (especially in the case of double-doubles) and also along rather different axes where some precession of the axis has taken place as discussed in the next section. Further investigation might reward us with a more detailed understanding of how supermassive black holes are fed from their environments.

4. Episodic jet activity in quasars: "new direction" examples

Erlund et al. (2006) found that there is considerable extended X-ray emission associated with the powerful radio galaxy 3C294; this is reproduced in Figure 3. The bulk of the X-ray emission shows extension along an axis differently oriented from the radio axis by ~ 50 degrees, and slightly longer than the length of the radio axis. Erlund et al suggest that the offset between these two axes arises because of the precession of the axis along which jet plasma is ejected. The fact that the superposed radio and X-ray observations reveal *intermittent* jet activity comes from the fact that for the two discrete directions indicated, one of them is traced by freshly accelerated high-energy radio-synchrotron emitting particles while the other direction appears to be consistent with inverse-Compton scattered CMB (ICCMB) photons (having a power-law $\Gamma = 2.1 \pm 0.1$). [Note that attributing the extended X-ray emission to X-ray synchrotron would require a very spatially extended acceleration mechansim for which no evidence has previously been seen or invoked: the radiative lifetime of X-ray synchrotron emitting particles is very short ($\lesssim 100$ years).] Consistent with the notion that the jet axis is precessing is the observation revealed in the zoom-in to Figure 3, that at high resolution the radio axis is offset from the nearby fine scale X-ray emission.

More recently, Steenbrugge & Blundell (2008) and Steenbrugge et al. (2008) have analysed superimposed X-ray and radio observations of the prototypical

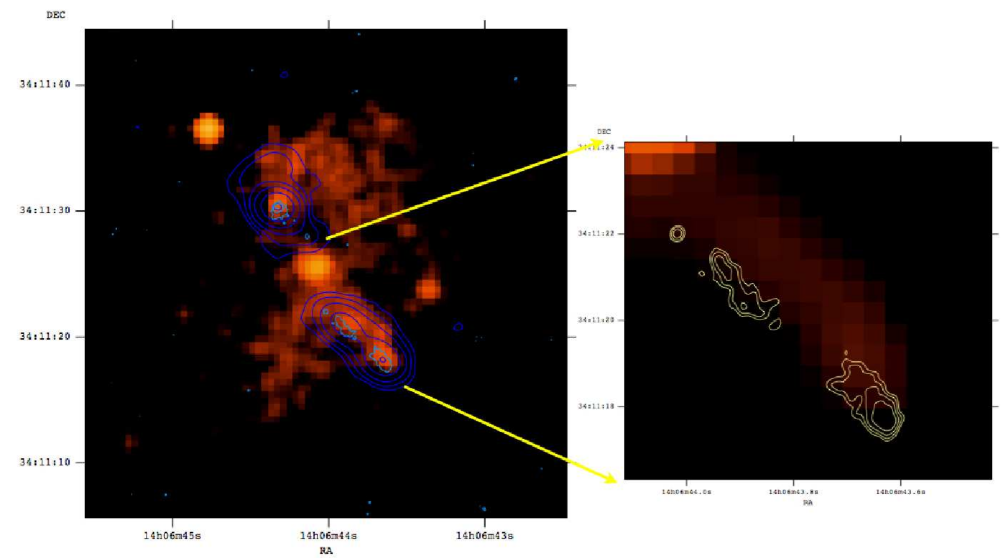

Figure 3. The powerful radio galaxy 3C294 ($z = 1.786$) observed in X-rays (greyscale) and radio (contours). Further figures are analysed by Erlund et al. (2006).

FRII radio galaxy Cygnus A and identified, from the co-addition of all relevant observations from the Chandra archive, a linear feature in X-rays. This feature easily satisfies the Bridle & Perley (1984) criteria for classification as a jet, and its energy spectrum is power-law (rather than thermal). For these and other reasons, Steenbrugge et al. (2008) interpret this linear feature as a relic jet, albeit along a somewhat different direction from that delineated by synchrotron radio emission. Figure 4 depicts as contours the radio synchrotron emission (the radio counter-jet is the most southerly of the radio emission, other than the East hotspot) while the relic X-ray counterjet is seen just to the north of this. Steenbrugge & Blundell (2008) present an analysis of the variations in the directions of the jets in terms of a precession of the launch axis of the jet ejecta.

Both 3C294 and Cygnus A show evidence of a different launch direction of jet ejecta revealed by the presence of low-energy (Lorentz factor 10^3) particles giving rise to ICCMB. There are other radio sources that may show evidence of a different jet axis, with both axes being revealed at radio wavelengths. These are the so-called winged or X-shaped radio sources and examples of this class are 3C403 and 3C223.1; these have been studied by Dennett-Thorpe et al. (2002) who favoured a fast, symmetric realignment of the jet axis on a timescale of a few Myr in these objects (although see Kraft et al. (2005) who reach a different view).

5. Precession versus Scheuer's dentist's drill: more than a semantic distinction?

Precession, of course, in its most general sense includes any change of the instantaneous spin axis. Generally defined precession includes the entire spectrum of

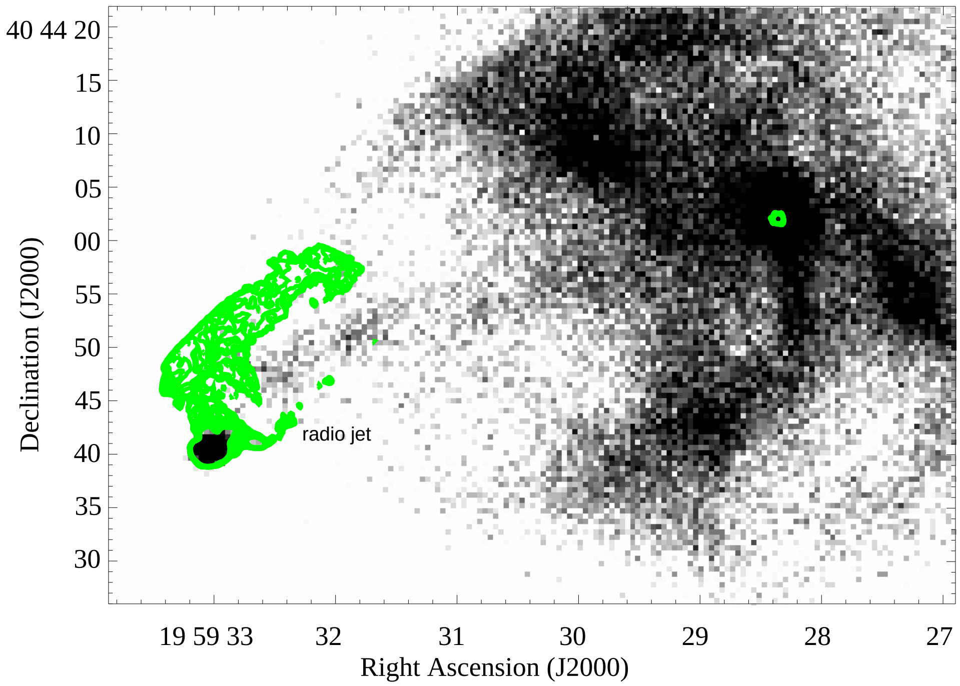

Figure 4. Images of Cygnus A in X-rays (greyscale) and 5-GHz radio (contours) of the part of it mainly pointing away from Earth. Further figures and analysis of its previous jet activity and variation in the jet axis are in Steenbrugge & Blundell (2008) and Steenbrugge et al. (2008).

spin-axis variations from polar wandering and nutation to Earth's Chandler wobble. All of these examples of precession are fundamentally two-sided (applying to the emerging jet and counterjet equally and simultaneously in the rest-frame of the nucleus). Temporal variation in precession parameters, as long as two-sided and instigated at the jet launch point by angular momentum changes (e.g. caused by variation in the fuelling), are properly described as precession and are distinct from Scheuer's (1982) Dentist's Drill phenomenon. That phenomenon is a response of a jet, on *one side* of a source, to local conditions (for example, buoyancy effects corresponding to local motions or inhomogeneities); Figure 5 is a reminder that dentists' drills on Earth are one-sided.

If deviations in jet-direction are neglected, and dismissed merely as a dental drill meandering, there exists the possibility that significant two-sided (symmetric) reorientations are overlooked. Symmetric direction change might arise from varying angular momentum in the matter being accreted by the supermassive black hole.

I remark that (symmetric, two-sided) precession of jet axes can of course occur without this precession being as steady or periodic as in the remarkably persistent case of the microquasar SS433 (Hjellming & Johnston 1981).

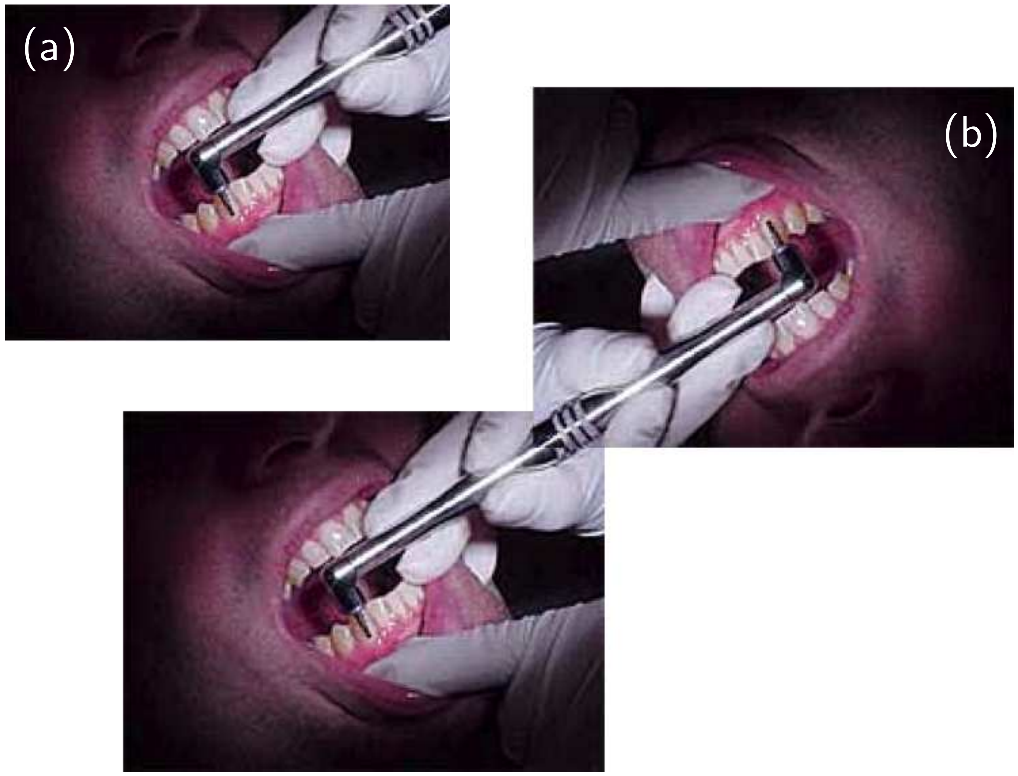

Figure 5. (a) The dentists' drill model in its originally conceived one-sided form, devised by Scheuer (1982). (b) A less-plausible, 2-sided version used by an imaginary dentist.

5.1. Two modes of energy loss: (I) the flaring mode (jets)

Blundell & Rawlings (2000, 1999) have presented evidence (from physical arguments and from the observed near-absence of any dead radio galaxies) that lobe emission must disappear on relatively rapid timescales, as mentioned in Section 1. In the light of the relatively rapid disappearance of radio lobes when jets are switched off, it is interesting to consider that the residual lobe-less quasars may be conveniently identified with radio-quiet quasars.

Nipoti et al. (2005) suggested a parallel between radio-loudness in quasars and the flaring mode (i.e. jet-ejecting mode) in microquasars, and hence an association of radio-quiet quasars with non-flaring states of microquasars. This is in agreement with the suggested association of radio-quiet AGN with 'high/soft' states (Maccarone, Gallo & Fender 2003), but it conflicts with the association (Falcke, Körding & Markoff 2004) of FR I radio sources with low-hard states (small accretion rate and steady radio emission).

5.2. Two modes of energy loss: (II) the coupled mode (cores)

Nipoti et al. (2005) suggested that the radio emission in quasars that is associated with the 'coupled' mode identified for microquasars, is confined to core (i.e. nuclear) emission from quasars, and is most readily detectable at GHz frequencies. Indeed, this radio core emission is observed from many quasars classified as radio-quiet (Blundell & Beasley 1998). They suggested that the 'flaring' mode leads to the formation of the large-scale (> kpc) jets that are the hallmark of radio-loud quasars, be they FR Is or FR IIs.

Recently, Blundell & Kuncic (2007) advanced a new, physical model for the radio emission from the cores of radio-quiet quasars (the 'coupled' mode in Nipoti et al's picture) that is significantly different from models related to the notion of a cosmically conspiritorial sequence of synchrotron self-absorbed jet knots originally advanced by Cotton et al. (1980). Radio emission from radio-quiet quasars is very weak and, if present, is confined to the nucleus or core region; it has been revealed by milli-arcsecond scale imaging techniques to arise from regions no larger than a few cubic parsec in extent (Blundell & Beasley 1998).

Blundell & Kuncic's (2007) model posits that optically thin bremsstrahlung from a slow, dense disc wind can make a significant contribution to the observed levels of radio luminosity arising from the unresolved cores of radio-quiet quasars. This model was inspired by observations of resolved disc wind emission observed directly via milli-arcsecond radio imaging of SS433 (Blundell et al. 2001; Paragi et al. 2002). If this thermal disc wind model turns out to be widely applicable for radio-quiet quasars, it will explain the long standing conundrum that radio-quiet quasars are strongly accreting yet lack the very obvious means of mass-loss and angular momentum-loss via directional jets: on the contrary, mass-loss via on-going disc winds accompanies persistent disc accretion.

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