A&A manuscript no.
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01(11.01.2; 11.10.1; 11.14.1; 02.01.2)

ASTRONOMY
AND
ASTROPHYSICS
29.6.1995

Unified schemes for active galaxies: a clue from the missing Fanaroff-Riley type I quasar population

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To appear in A&A

Abstract. We link the lack of FR I type structure among quasars to the void of radio loud quasars below a critical disk luminosity of $\sim 10^{46}$ erg/sec in the PG sample. We argue that the opening angle of the obscuring torus in radio loud quasars depends on the power of the central engine, approaching the jet's beaming angle near the FR I/FR II break. Consequently, low power radio quasars would either be classified as radio galaxies (FR I) or strongly core-boosted (BL Lac) object, depending on the aspect angle, and no conspicuous transitional population would be expected for FR I sources. A closing torus with decreasing power would not only obscure the optical nucleus for most aspect angles but would also enhance the entrainment of the cool torus material into the jet stream, causing obscuration along the jet's periphery, as well as the jet's deceleration to form a FR I source. Above a critical luminosity, the wider torus allows for FR II type jets and visibility of the nuclear optical emission, characteristic of radio loud quasars. Apparently, at the same engine power the torus opening in radio weak quasars and Seyferts is substantially wider than in radio loud quasars, probably because of different dynamics or feeding mechanisms in disk and elliptical galaxies. This provides a clue for the radio-loud/radio-quiet dichotomy of quasars if the the jet/torus interaction leads to injection of relativistic $e^{\pm}$ via *pp* collisions. Strong jet/torus interaction may lead to a substantial injection of secondary pairs and collimation in radio loud quasars, while weak interaction in radio weak quasars leads neither to pair injection nor to good collimation.

Key words: galaxies: active – galaxies: jets – galaxies: nuclei – accretion disks

1. Introduction

The different manifestations of energetic phenomena (radio jets and non-stellar optical emission) in active galactic nuclei (AGN) have provoked attempts to unify several different classes of AGN, by arguing that a pair of relativistic jets and a coaxial obscuring torus can yield radically different views of the same object, depending upon the aspect angle (see reviews by Antonucci 1993; Gopal-Krishna 1994). Observations by Lawrence & Elvis (1982), Mushotzky (1982) and Antonucci & Miller (1985), suggested that Seyfert 2 galaxies are simply Seyfert 1 galaxies where an obscuring torus blocks a direct view of the nuclear region. Several authors (e.g. Barthel 1989) extended this and identified the powerful narrow-line radio galaxies of Fanraroff-Riley type II (FR II, edge brightened) as the misaligned parent population of radio loud quasars, while the core-dominated, rapidly variable quasars ('blazars') represent the cases of close alignment between the jet and the line-of-sight. Following Blandford & Rees (1978), BL Lac objects are identified as the boosted counterparts of intrinsically weaker Fanaroff-Riley type I (FR I, edge darkened) radio galaxies (e.g. Urry et al. 1991).

Despite the consensus that both FR I and FR II galaxies are associated with massive ellipticals, it has been argued that they are distinct phenomena (e.g., Heckman et al. 1994) and hence, the unified schemes for FR I and FR II sources would bear no direct relationship. On the other hand, it has also been suggested that the two morphological types may have a physical, perhaps evolutionary connection (e.g., Owen & Ledlow 1994). Also, it has been recently argued that AGN of all radio powers, including those as weak as the Galactic Center source Sgr A* (Falcke et al. 1993a&b, Falcke 1994a&b), have basically similar central engines, i.e. a closely coupled jet/disk system around a black hole, and the apparent differences are caused largely due to interaction with the parsec-scale environment (Falcke & Biermann 1994 (FB94); Falcke, Malkan, Biermann 1994 (FMB)).

Clearly, finding a common ground between the two unification schemes (FR I radio galaxy-BL Lac and FR II radio galaxy-quasar-blazar) would be a consolidating step forward. One observation that stands in the way of such a reconciliation is the persistent lack of unambiguous examples of FR I type quasars. Here we examine this point closely, using a well defined sample of optically selected quasars and propose that a *closing torus*, rather than fundamentally different types of engines might be responsible for the striking rarity of FR I quasars *and* for the FR II/FR I transition.

2. The 'void' of radio-loud quasars

Although the basis of the unified schemes proposed for FR I and FR II radio sources is essentially the same relativistic jet phenomenon in the nucleus, the two schemes differ in that, unlike the FR II scheme, the FR I scheme does not have to contend with a 'transitional population' between the parent population (radio galaxies) and its strongly Doppler-boosted subset (BL Lacs). From radio imaging surveys, this point has been noted in the past (e.g., Perlman & Stocke 1993) and can be perceived more clearly by considering the radio morphological content of a large sample of optically-selected quasars, e.g. the PG quasar sample (Schmidt & Green 1983). In one such study using the VLA (A-array), Miller et al. (1993) investigated the radio morphologies of the $z < 0.5$ quasars in the PG sample. Out of the total 89 quasars 13 can be classified as radio-loud and all of them resemble a FR II morphology, consistent with their high radio luminosities. As seen from their Fig. 2, the total luminosities of the 13 radio-loud quasars are clustered in a narrow range between 10^{32} and 10^{33} erg/sec/Hz/ster at 5 GHz. Below this limit, for two decades in luminosity, a conspicuous gap is present in which not a single radio loud quasar possessing resolved radio emission (potentially FR I morphology) is found. A sharp drop in the radio-loud fraction of quasars has also been noted to occur below $M_{\rm B} \sim -24.5$ (Padovani 1993).

This pattern is clearly illustrated in Fig. 1 which shows for the same $z < 0.5$ subset of the PG sample a plot of radio *core* luminosity vs. disk luminosity, $L_{\rm disk}$. To estimate the latter, we combined accretion disk fits, emission line luminosities and continuum fluxes and obtained an average value for each quasar (FMB). Although the region below a critical $L_{\rm disk} \lesssim 10^{46}$ erg/s contains 68 quasars, not a single example of a typical, lobe-dominated radio source is found there. Thus, intrinsic weakness of the nuclear ionizing radiation, or any related selection effect can not be the reason for this void. The existence of a 'critical' $L_{\rm disk}$ is, in fact, reminiscent of the 'break' in the radio luminosity function of E/SO galaxies, below which powerful radio sources (FR II) become rare and the weaker FR I type sources begin to predominate (Fanaroff & Riley 1974) – in fact the *total* power at 5 GHz of the weakest FR II PG quasar ($2 \cdot 10^{42}$erg/sec) is very close to the FR II/FR I break at $\sim 10^{42}$erg/sec. The morphological transformation at this break was proposed to be due to the effect of the hot gaseous halo of the parent elliptical galaxy on the advancing jet. Below the critical power, the external medium decelerates the jet at an early stage to subsonic velocities, leading to a rapid decollimation and enhanced mass entrainment, all resulting in radio fading and FR I morphology (Gopal-Krishna 1991; Roland et al. 1992; Bridle 1992). Jets above the critical power would continue to propagate supersonically and terminate far away in a strong shock producing compact hot spots. In this picture, the jets responsible for the two morphological types are not required to be basically different *ab initio*.

According to the above scenario for FR II to FR I transition with decreasing source power, and considering that the jet and the UV bump are both produced by the same engine (e.g. FMB), one might naively expect a similar transition to occur also in the case of quasars: a lower accretion power would presumably yield both a lower disk luminosity and a weaker jet (FB94) and thus below a critical disk luminosity of $L_{\rm disk} \lesssim 10^{46}$ erg/sec FR I quasars should be found. Apparently, this does not happen; the disappearance of FR II quasars below the critical disk luminosity is not accompanied by an emergence of a FR I quasar population (Fig. 1). It may be noted that the appearance of the latter in Fig. 1 would, in fact, be facilitated by the fact that compared to FR II sources, the radio cores in FR I sources are relatively more prominent (Bridle 1992). It can therefore be surmised that *the void of radio-loud quasars below* $L_{\rm disk} \lesssim 10^{46}$ *erg/sec is in fact the void of FR I quasars.*

3. Approach to harmonise the two unified schemes

Does the lack of FR I quasars, in contrast to the abundance of FR I galaxies, imply that they are different types of systems? Or, alternatively, do FR I quasars also exist, but are not classified as such? Here we argue for the latter by examining the possible connection between the power of the central engine/jet and the obscuring torus. From the optical identification content of the 3CRR complete sample of radio sources, a systematic increase in the fraction f of the broad-lined objects and, therefore, in the opening angle of the putative torus with radio luminosity can be inferred (Lawrence 1991). The trend appears to be systematic and with a reasonably high statistical significance — though reclassification of some objects may eventually change the numbers slightly. Furthermore, a corraborative evidence for this trend comes from the optical identification content available for yet another complete sample of radio sources, namely, the 1-Jy sample defined by Allington-Smith (1982; see Singal 1993). It can thus be inferred that, on average, the bi-conical openings of the torus shrink steadily with decreasing power of the central engine. From Fig. 2b of Lawrence (1991), the half-opening angle (ψ) is estimated to be typically in the range 45° to 60° for powerful (FR II) sources. Further, although the observed decrease in f to $\lesssim 0.1$ near the FR I/FR II break still allows for a significant population of broad-lined objects even at these modest luminosities, it translates

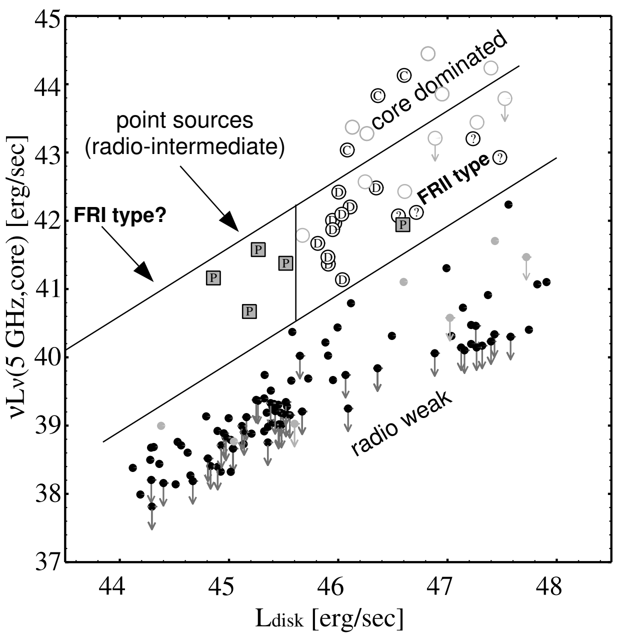

Fig. 1. Radio core luminosity vs. the disk luminosity of PG quasars. Below $L_{\rm disk} \sim 10^{46}$ erg/sec no radio loud quasars of FR II type are found (see FMB for details) – *open circles*: radio loud quasars, 'D' marks FR II morphology and 'C' marks core dominated quasars; *dots*: radio weak quasars; *boxes*: variable flat spectrum points sources, interpreted as boosted radio weak quasars; *grey symbols:* non-PG quasars from the extended sample of FMB.

to a ψ of $\lesssim 25°$ which with decreasing power below the break approaches quickly the typical beaming angle of the jets. Consequently, a direct view of the nuclear region in moderately powerful (FR I) radio sources – a pre-requisite for quasar classification – would be unavoidably accompanied by a strongly Doppler-boosted appearance of the synchrotron jet. Due to this and the enhanced obscuration of the nuclear region caused by the jet- entrained torus material (Sect. 4), the aligned FR I sources would generally end up being classified as BL Lacs. Cases of an intermediate jet-alignment would indeed appear less core-dominated but the nuclear region would be directly obscured by the torus with narrow openings at these modest powers, leading to a (FR I) galaxy classification. The lack of a transitional, FR I quasar population can thus be understood (Gopal-Krishna 1994) without invoking any conceptual difference between the unified schemes for FR I and FR II.

4. Jet interaction with a closing torus

According to the current understanding, continually accreted molecular clouds with a wide range in size form a major constituent of the dusty torus (Krolik & Begelman 1988). Being directly irradiated by the energetic photons from the central engine, the inner walls of the torus are steadily stripped, forming an outflowing wind filling the torus openings (e.g., Balsara & Krolik 1993). In highly luminous sources, the wind filling the funnels is likely to consist of hot plasma whose thermal pressure could even contribute substantially to the jet's confinement on the parsec scale as required in some models (e.g. Appl & Camenzind 1993). The interaction between the jet and the dense torus material would be more direct in lower power sources with narrower torus openings – especially when ψ approaches the jet's opening angle. The material stripped from the torus walls and entrained into the jet flow would then rapidly decelerate it to low Mach numbers and a trans-sonic FR I type flow, leading eventually to the jet's disruption and consequent fading of the radio lobes, as discussed in the models of Bicknell (1994) and De Young (1993). As the entrained clouds would tend to occupy the peripheral region of the jet's cross section, the boosted nonthermal radiation from the jet's core would escape essentially unobscured by the clouds. However, the optical/UV emission from the outer regions of the jet and especially from the nuclear disk surrounding the jet near its base (into which the broad- line-emitting clouds seem to be concentrated; cf. Wills & Browne 1986) would probably be strongly obscured. Thus, a closing torus with decreasing engine power could cause the obscuration of the nuclear optical line and UV emission, *as well as* the transition from a FR II to FR I morphology. This could explain why the radio morphological transition occurs at a power similar to where the radio loud quasars practically disappear (Fig. 1). Further, the existence of a critical optical/radio power for the FR I/FR II break indicates that the power-dependence of ψ is probably linked to the interaction with the jet. A stronger jet-torus interaction could well be responsible for the observational result that in radio galaxies the jet appears systematically more prominent with decreasing total radio power (Bridle 1992).

Here, we mention a specific mechanism by which a locally enhanced synchrotron emissivity could arise during a strong interaction of the jet with a dense torus. It was argued from synchrotron and Compton loss arguments (e.g. FB94) that in order to explain the high efficiency of radio loud jets in a coupled jet/disk system additional relativistic electrons have to be injected at the $0.1 - 1$ pc scale. A possible mechanism for the radiation enhancement would be $e^{\pm}$ pair production in hadronic cascades following *pp* collisions of relativistic protons (Biermann & Strittmatter 1987; Sikora et al. 1987) with fragments of the dense material in the torus funnel or in the shear layer between the jet and the ambient medium. Although $e^{\pm}$ pairs in the jets are generally thought to arise primarily from electromagnetic processes near the center, the possibility of a substantial contribution from hadronic cascades has been defended recently on energetic grounds, since such collisions would naturally yield a low energy cut-off around $50 - 100$ MeV (FB94, Biermann et al. 1994), as inferred from independent arguments (Wardle 1977, Celotti & Fabian 1993).

5. Radio-weak quasars

While the FR I/FR II radio galaxies and radio-loud quasars are almost exclusively hosted by ellipticals, most radio-quiet quasars and Seyfert nuclei appear to reside in disk galaxies (e.g. McLeod & Rieke 1994). The small number of luminous Seyfert 2 (quasar 2) (Osterbrock 1991), the rarity of highly polarized Seyfert 2 (Miller & Goodrich 1990) and the evidence for a declining covering factor of the central engine with increasing luminosity (e.g., Lawrence & Elvis 1982; Reichert et al. 1985) have led to the speculation that the torus-opening in Seyferts and quasars becomes wider with increasing power of the engine. From Sect. 2 and 3, we inferred that even at a disk luminosity as high as 10^{46} erg/sec, the torus in radio-loud AGN is practically closed, whereas it is already wide open in the case of radio-weak AGN (ψ approaching 60°; see, McLeod & Rieke 1994; Dunlop et al. 1993). Even in exceedingly radio-weak AGN, like Seyferts, the typical value of ψ is still quite large (about 30°, e.g. Pogge 1989). From this we infer that for a given power of the central engine, radio-weak AGN can maintain a wider torus opening. This is perhaps a result of higher specific angular momentum expected for the nuclear tori within their host (disk) galaxies. Since ellipticals with AGN are thought to be merger products (e.g., Barnes & Hernquist 1993), a significant cancellation of the angular momentum of the progenitors can occur, in contrast to spirals where the gas is probably accreted from the disk, stirred up by starbursts (Biermann et al. 1993). Camenzind (1993) has suggested that tori with narrow opening angles could be due to the substantially larger core radii in ellipticals. It is tempting to speculate that a wider torus opening in disk galaxies leads to a poor confinement of the jet and a further loss of radio emissivity via strongly diminished injection of secondary pairs in hadronic cascades due to a weaker jet-torus interaction and less *pp* collisions. A poorly confined jet ejected from a disk would be slowed down much earlier, producing diffuse, radio-inefficient lobes in radio weak quasars (Miller et al. 1993). Thus, a different type of torus in disk galaxies could be a significant factor contributing to their radio weakness.

6. Conclusions

Using the PG sample of QSOs, we have argued that the near absence of quasars with FR I type radio morphology could be a direct consequence of the reported trend for the torus to be wider open in more luminous radio sources. Near a critical disk luminosity ($\sim 10^{46}$ erg/s), the torus narrows down to roughly the beaming angle of the relativistic jet (10° to 15°), inhibiting a direct view of the nuclear region without the appearance of a strongly Doppler-boosted (BL Lac like) synchrotron jet. Moreover, below this power, a further shrinking of the funnels would cause a direct interaction of the jet with the torus, triggering the transition from an FR II to FR I morphology. This transformation would be accompanied by an increased obscuration of the optical line and continuum emission from the nuclear disk by the dense torus material entrained in the jet flow. Collisions of relativistic protons in the boundary layer between jet and torus funnel could locally enhance the synchrotron output of the jet and, hence, its prominence by injecting secondary pairs in hadronic cascades (Fig. 2). Consequently, there seems to be no need for conceptually different unification schemes for FR I and FR II.

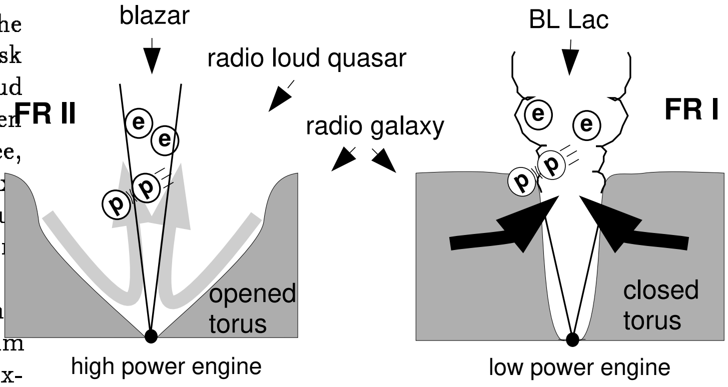

Fig. 2. Sketch of the proposed scheme: a low-power (FR I) jet is slowed down by a closing torus which also obscures the central engine while a high-power (FR II) source with open torus appears as a quasar for some aspect angles. Hadronic cascades might produce additional relativistic pairs in the interaction zone.

The critical disk power of $\sim L_{\rm disk} \sim 10^{46}$ erg/s in ellipticals where the torus appears closed apparently is a few orders-of-magnitude higher than the corresponding value for spirals. Thus, the intrinsically wider torus at the same engine power in spirals would result in a fainter jet due to poor confinement and weaker jet-torus interaction causing a diminished injection of secondary $e^{\pm}$ into the jet. It appears plausible that the type of the host galaxy is more important in determining the shape of the torus, rather than the much smaller region dominated by the black hole. Hence, *intrinsically different tori at the pc scale, rather than intrinsically different central engines* might play a critical rôle for the radio loud/radio-weak quasar dichotomy and the FR I/FR II separation.

A key question for future work would be the formation and stability of tori in different types of host galaxies. Papaloizou & Pringle (1985) found that thick accretion disks have unstable modes, which, however, depend on the boundary conditions at the edge of the disk (Goldreich et al. 1986) – a powerful jet could strongly influence this result. The torus could also fragment into clouds (Hawley 1987), yielding a configuration similar to the Krolik & Begelman (1988) torus composed of molecular clouds, but the stability and structure of the latter for very small ψ remain unclear. The reason for the power dependence of ψ could well be the jet/torus interaction but also radiation pressure or a changing disk structure with accretion rate.

Further observational consequences are expected in the high energy regime, i.e. production of X-rays and gamma-rays (see also Mannheim 1993) and in the infrared (IR). Since the torus in FR II already intercepts more than half of the central luminosity, only a marginal increase in the fraction of nuclear radiation reprocessed into the IR is expected for FR I. However, due to the different shapes of their torus-funnels, spectral differences in the IR are possible. One also expects to find the ionization cone associated with FR I aources to be quite narrow. In case the radio weak quasars, too, eject relativistic jets one ought to find their boosted counterparts (RIQs, see FMB).

Acknowledgements. HF thanks L. Saripalli for stimulating discussions on the puzzling lack of FR I quasars. We are grateful to the referee Dr. M. Salvati for helpful suggestions.

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