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BLACK HOLE, JET, AND DISK: THE UNIVERSAL ENGINE

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Abstract: In this paper I review the results of our ongoing project to investigate the coupling between accretion disk and radio jet in galactic nuclei and stellar mass black holes. We find a good correlation between the *UV bump luminosity* and the radio luminosities of AGN, which improves upon the usual [OIII]/radio correlations. Taking mass and energy conservation in the jet/disk system into account we can successfully model the correlation for radio-loud and radio-weak quasars. We find that jets are comparable in power to the accretion disk luminosity, and the difference between radio-loud and radio-weak may correspond to two natural stages of the relativistic electron distribution – assuming that radio weak quasars have jets as well. The distribution of flat- and steep-spectrum sources is explained by bulk Lorentz factors $\gamma_{\rm j} \sim 5-10$. The absence of radio-loud quasars below a critical optical luminosity coincides with the FR I/FR II break and could be explained by a powerdependent, "closing" torus. This points towards a different type of obscuring torus in radio-loud host galaxies which might be a consequence of past mergers (e.g. by the temporary formation of a binary black-hole). Interaction of the jet with the closing torus might in principle also help to make a jet radio-loud. Turning to stellar-mass black holes we find that galactic jet sources can be described with the same coupled jet/disk model as AGN which is suggestive of some kind of universal coupling between jet and accretion disk around compact objects.

1 Introduction

1.1 The AGN zoo

Non-stellar activity in galactic nuclei is generally thought to be produced by a powerful engine located at the dynamical center of the galaxy. Because of the high luminosity of active galactic nuclei (AGN) concentrated in a small volume, it has been argued that those engines are powered by accretion onto a massive black hole. To the pleasure of observers this activity appears in many different forms and flavors which has led to a proliferation of object classes based on specific properties in one or the other wavelength band. The most important ones are:

a) *Seyfert galaxies* of type 1 (narrow and broad emission lines) and type 2 (narrow lines only) with luminosities up to several 10^{44} erg/sec, corresponding to accretion rates of $\lesssim 10^{-2} M_\odot$/yr
b) *Quasars*, with broad and narrow emission lines and a peak in their spectral energy density distribution (SED) in the UV ("UV bump"), the luminosities are in the range $10^{44..48}$ erg/sec corresponding to accretion rates of $10^{-2..+2} M_\odot$/yr, some quasars have strong radio emission and are labeled radio-loud, otherwise radio-weak (or quiet)
c) *Radio galaxies*, with powerful jets, steep-spectrum radio lobes and compact, flat-spectrum cores; low-power sources have edge-darkened, smoke-trail like lobes (FR I) while high-power sources have well collimated jets and terminate in hotspots (FR II), the optical spectrum of the core usually shows only narrow emission lines
d) *Blazars*, sources completely dominated by variable, non-thermal (synchrotron) emission from a compact core (BL Lacs), if a quasar spectrum is still seen then one has a highly polarized quasar (HPQ) or optically violently variable (OVV), those sources have the highest probability of showing high-energy ($\gtrsim$GeV) emission.

In summary, the different signs of nuclear activity, which are rarely seen in one object together (except perhaps 3C 273), are: a luminous thermal bump in the SED, broad and narrow high-excitation emission lines, a compact radio core, a powerful radio jet and lobes, and variable high-energy (x-ray to gamma-) emission.

1.2 The unification

The diversity of objects has provoked the foundation of a "unification church"[1] (Antonucci 1993 and refs. therein, see also Antonucci – this volume) and a sporadic Counter-Reformation which, however, has not yet rallied its forces effectively. The ingredients to make the unification work are relativistic beaming in a jet and obscuration of the central engine by a molecular torus such that objects appear different if seen from different aspect angles: a Seyfert 1 galaxy becomes

[1] This religious allusion appears reasonable considering that both ideas – despite being basically correct – are seemingly not accessible through reasoning but require the experience of a personal conversion.

a Seyfert 2 by obscuration, a radio-loud quasar becomes a FR II radio galaxy by obscuration and an HPQ by beaming, likewise a FR I radio galaxy becomes a BL Lac by relativistic beaming.

A third ingredient to unify object classes, which I consider very important but is seldom mentioned explicitly, is the power (or in the black hole picture the accretion rate) of the nuclear engine. Thus, by increasing the power, normal galaxies might turn into Seyferts and then into quasars, provided that the majority of normal galaxies has a central black hole. As the FR I/FR II separation is by morphologhy *and* power, it is likely that by decreasing the accretion rate, a FR II radio galaxy turns into an FR I and then into a quiescent elliptical. Even though this already gives a pretty and simple picture, a few fundamental questions remain: a) if high-power (FR II) galaxies and quasars, and FR I and FR II are connected, how are low-power (FR I) and quasars/Seyferts connected, and b) what makes the difference between a radio-loud and a radio-weak AGN (the $1,000,000 question)? Remembering that radio-loud AGN occur only in elliptical galaxies, the latter question is even more tantalizing. Finally, it should be realized, that the influence of source evolution is difficult to assess; shape and size of the obscuring torus may well depend on the evolutionary stage of the AGN and the host galaxy.

1.3 The universal engine – a *simple* Ansatz

If the central engine is indeed associated with a black hole, it has the unpleasant property of being so small that it is almost inaccessible by observational means and hence open to wild theoretical speculations. Currently there is no way to prove or disprove that all central engines are completely different or absolutely identical and one is forced to choose a basic Ansatz for the nature of the engine which allows one to draw further conclusions and test them against observational data. Strangely, in Astronomy the burden of proof is usually on those who postulate a simpler solution (like the unified schemes) while Occam's Razor should force one to start with the simplest theory until experimentally disproved. Consequently our Ansatz for the nature of the central engines in AGN should be that those engines are all very similar and governed by a few parameters only. Such an engine would be a black hole which accretes matter within an accretion disk, producing a jet at the black hole/disk boundary layer flowing out along the rotation axis (alternative engines are discussed in the contributions by Scheuer, Kundt, and Sorrell – this volume). As the escape speed from a black hole is relativistic, those jets would have to be relativistic as well, as the jets are produced by the disk, one expects a strong coupling between jet and disk, and as most of the power in an accretion disk is relased close to the center, the jet can be very powerful, and finally, as "a black hole has no hair", there are not many parameters that can vary from one engine to another, and the main parameter of the engine is expected to be the accretion rate. This "simple Ansatz" also implies that jets are a natural companion to accretion disks, and both are necessary and symbiotic features in the accretion process onto the compact central object (Falcke & Biermann 1995; hereafter FB95).

2. Jet-disk coupling

A coupled jet-disk system has to obey the same conservation laws as all other physical systems, i.e. energy and mass conservation. We can express those constraints by specifying that the total jet power $Q_{\rm jet}$ is a fraction $2q_{\rm j} < 1$ of the accretion power $Q_{\rm disk} = \dot{M}_{\rm disk}c^2$, the jet mass loss is a fraction $q_{\rm m} < 1$ of the disk accretion rate $\dot{M}_{\rm disk}$, and the disk luminosity is a fraction $q_{\rm l} < 1$ of $Q_{\rm disk}$ ($q_{\rm l} = 0.05 - 0.3$ depending on the spin of the black hole). The dimensionless jet power $q_{\rm j}$ and mass loss rate $q_{\rm m}$ are coupled by the relativistic Bernoulli equation (FB95). For a large range in parameter space the total jet energy is dominated by its kinetic energy such that one has $\gamma_{\rm j}q_{\rm m} \simeq q_{\rm j}$, in case the jet reaches its maximum soundspeed $c/\sqrt{3}$ the internal energy becomes of equal importance and one has $2\gamma_{\rm j}q_{\rm m} \simeq q_{\rm j}$ ('maximal jet'). The internal energy is assumed to be dominated by the magnetic field, turbulence and relativistic particles. We will constrain the discussion here to the most efficient type of jet where we have equipartition between the relativistic particles and the magnetic field and between internal and kinetic energy – we will later see that other, less efficient models (see FB95) would fail.

Knowing the jet energetics, we can describe the longitudinal structure of the jet by assuming a constant jet velocity (beyond a certain point) and free expansion according to the sound speed ($\simeq c/\sqrt{3}$). For such a jet, the equations become very simple, the magnetic field is given by

$$B_{\rm j} = 0.3\,G\,Z_{\rm pc}^{-1}\sqrt{q_{\rm j/l}L_{46}}$$

and the particle number density is

$$n = 11\,{\rm cm}^{-3}L_{46}q_{\rm j/l}Z_{\rm pc}^{-2}$$

(in the jet restframe). Here $Z_{\rm pc}$ is the distance from the origin in pc, L_{46} is the disk luminosity in 10^{46} erg/sec, $2q_{\rm j/l} = 2q_{\rm j}/q_{\rm l} = Q_{\rm jet}/L_{\rm disk}$ is the ratio between jet power (two cones) and disk luminosity which is of the order 0.3 (FMB95) and $\gamma_{\rm j,5} = \gamma_{\rm j}/5$ ($\beta_{\rm j} \simeq 1$). If one calculates the synchrotron spectrum of such a jet, one obtains locally a self-absorbed spectrum that peaks at

$$\nu_{\rm ssa} = 20\,{\rm GHz}\,\mathcal{D}\frac{\left(q_{\rm j/l}L_{46}\right)^{2/3}}{Z_{\rm pc}}\left(\frac{\gamma_{\rm e,100}}{\gamma_{\rm j,5}\sin i}\right)^{1/3},$$

integrating over the whole jet yields a flat spectrum with a monochromatic luminosity of

$$L_\nu = 1.3\cdot 10^{33}\,\frac{\rm erg}{\rm s\,Hz}\,\left(q_{\rm j/l}L_{46}\right)^{17/12}\mathcal{D}^{13/6}\sin i^{1/6}\gamma_{\rm e,100}^{5/6}\gamma_{\rm j,5}^{11/6},$$

where $\gamma_{\rm e,100}$ is the minimum *electron* Lorentz factor divided by 100, and $\mathcal{D}$ the *bulk* jet Doppler factor. At a redshift of 0.5 this luminosity corresponds to an unboosted flux of ~ 100 mJy. The brightness temperature of the jet is

$$T_{\rm b} = 1.2 \cdot 10^{11}\,{\rm K}\,\mathcal{D}^{4/5} \left(\frac{{\gamma_{\rm e,100}}^2 q_{\rm j/l} L_{46}}{\gamma_{\rm j,5}^2 \beta_{\rm j}}\right)^{1/12} \sin i^{5/6}$$

which is almost independent of all parameters except the Doppler factor. An important factor that governs the synchrotron emissivity is of course the electron distribution, for which we have assumed a powerlaw distribution with index $p = 2$ and a ratio 100 between maximum and minimum electron Lorentzfactor. As we are discussing here the most efficient jet model we also assume that all electrons are accelerated (i.e. $x_{\rm e} = 1$ in FB95), hence the only remaining parameter is the minimum Lorentzfactor of the electron distribution $\gamma_{\rm e,100}$ determining the total electron energy content. In order to reach the magnetic field equipartition value, which is close to the kinetic jet power governed by the protons, we have to require $\gamma_{e,100} \sim 1$. It cannot be higher because otherwise the power in electrons would exceed the total jet power, and it cannot be much lower because we would not reach equipartition. Such a high, low-energy cut-off in the electron energy distribution was suggested already by Wardle (1977) and Celotti & Fabian (1993) for other reasons.

If radio-interferometric techniques were not yet developed today, and we would have been asked to predict what kind of jet sources we would expect to see, we would have needed only very few simple considerations:

a) *'total equipartition' everywhere*, i.e. equipartition between the luminosity radiated by the disk and expelled by a jet wind, equipartition between internal energy and kinetic energy, and equipartition between relativistic particles and magnetic field
b) *relativistic speed*, because, if the jet is produced close to the black hole, relativistic escape speeds are required,
c) *disk luminosity* (UV-bump), which is a measurable quantity

Thus, using $L_{\rm disk} \sim 10^{46}$ erg/sec and $\gamma_{\rm j} \sim 5$, we could have predicted pc-scale radio cores at cm-wavelengths, with brightness temperatures of 10^{11} K and fluxes of 100 mJy and more. But of course, nobody would have believed us as those assumptions are obviously too simplified...

3. UV/radio correlation

3.1 Estimating the disk luminosity

Now, we will have to validate some of our assumptions and test the jet-disk coupling derived above. For this we have to estimate the disk luminosity of quasars as precisely as possible and compare it to their radio cores. The best studied quasars sample so far is the PG quasar sample (Schmidt & Green 1983). For most sources in this sample Sun & Malkan (1989), using optical and IUE data, fitted the UV bump with accretion-disk models and a few more were available in the archive (Falcke, Malkan, Biermann 1995, hereafter FMB95). There are also excellent photometric (Neugebauer et al. 1987) and spectroscopic data (Boroson & Green 1992) available, but unlike the broadband UV-bump fits, emission lines and continuum colors do not give a direct estimate for the bolometric UV luminosity ($L_{\rm disk}$) and we need to calibrate those values to the UV bump luminosity using the sources which have a complete set of data available, yielding

$$\lg(L_{\rm disk}/{\rm erg\ s^{-1}}) = 2.85 + \lg(L_{\rm [OIII]}/{\rm erg\ s^{-1}}),$$
$$\lg(L_{\rm disk}/{\rm erg\ s^{-1}}) = 2.1 + \lg(L_{\rm H\beta}/{\rm erg\ s^{-1}}),$$
$$\lg(L_{\rm disk}/{\rm erg\ s^{-1}}) = -0.4M_{\rm b} + 35.90.$$

With those correlations one should be able to estimate the "disk luminosity" for almost any quasar. If several indicators are available, we can combine them (assigning appropriate weights) to get the final estimate, this then gives a fairly reliable estimate of $L_{\rm disk}$ and reduces the scatter in the correlations considerably as it also reduces the effects of the orientation dependence of some lines (e.g. [OIII]). In the next step, we can compare those disk luminosities with VLA radio cores (Kellermann et al. 1989, Miller et al. 1993) and total radio emission. In addition to the optically selected sample in FMB95 I have now also included quasars from the southern 2 Jansky sample (Morganti et al. 1994, Tadhunter et al. 1994) which are predominantly flat-spectrum quasars, and steep-spectrum, lobe dominated quasars from Bridle et al. (1994), Akujor et al. (1995), and Reid et al. (1995) which had emission lines readily available (Steiner 1981, Jackson & Browne 1991, Wills et al. 1993). Thus, the number of radio-loud quasars is increased considerably – the results are shown in Figures 1&2.

3.2 Different types of radio sources

For those kinds of optical/radio correlation it is very important what kind of radio source one is talking about. Here I distinguish between four cases represented by different symbols: a) radio-weak quasars with weak, diffuse or unresolved radio emission, b) core dominated, flat-spectrum sources, c) FRÍI type steep spectrum sources, and d) compact steep spectrum (CSS) or irregular radio sources. It is quite obvious that the radio/optical correlation may be very different for all these sources – at least in total flux. CSS and irregular sources usually have jets which are strongly interacting with a dense environment inside the galaxy, and their radio output is expected to be strongly modified by this interaction. Flat spectrum sources are usually dominated by their relativistically boosted jet with the inclination being a very sensitive parameter and cannot be compared with the steep-spectrum emission of lobe-dominated sources, and finally steep-spectrum radio-loud and regular radio-weak sources have a completely different radio morphology and hence must also be treated separately.

This is highlighted in Fig. 1, where one can see that radio-loud and radio-weak sources are clearly separated. The undisturbed, steep-spectrum FR II sources do show a relatively tight correlation, the CSS and irregular quasars scatter around and do not show any correlation, and the core-dominated sources are mainly located at the upper end of the radio distribution consistent with being relativistically boosted – with the exception of a few radio-intermediate quasars (RIQ) located in the gap between radio-loud and radio-weak quasars.

Fig. 1. Total radio luminosity vs. disk (UV-bump) luminosity for quasars (including a complete optical and a radio-selected sample). The shaded circles are core-dominated, flat-spectrum sources, open circles are steep-spectrum (FR II type) sources, circles labeled 'c' are CSS sources and filled points are radio-weak (diffuse or unresolved) sources. Only undisturbed radio-loud FR II type and radio-weak sources show a tight correlation. Flat-spectrum sources are boosted to the upper end of the distribution except 6 radio-intermediate quasars which might be boosted radio-weak quasars (see text). The total emission of CSS does not show a tight correlation with disk luminosity. The solid line is the (oversimplified) model for the lobes from FB95 (see also FMB95).

3.3 Boosted radio-weak quasars?

The RIQ in the gap are all optically selected PG quasars, and their radio fluxes are typically a few ten up to a few hundred mJy. From their R-ratio between radio and optical flux, they are neither clearly radio-loud nor clearly radio-weak, but all are unresolved with the VLA. Using the Effelsberg 100m telescope, we measured the fluxes of those sources at 11 and 2.8 cm to look for variability and spectral slopes (Falcke, Sherwood, Patnaik 1996, in prep.). Even though the data is not yet fully evaluated it is quite obvious that 6 of those sources have flat-spectrum cores and at least 5 are variable. In order to distinguish them from the 2 probable CSS sources which can also be found in the radio-intermediate 'gap', we will label them flat-spectrum radio-intermediate quasars (FIQ).

Some of the FIQ were known as variable sources before, e.g. III Zw 2 which varies between 40 mJy and 1 Jy at 5 GHz and has a brightness temperature probably well in excess of 10^{11}K (Teräsanta & Valtaoja 1994)– ususally a sign of relativistic boosting. The presence of a variable flat-spectrum radio core (without or with weak extended emission) alone is usually already regarded as a good sign for relativistic boosting. In FMB95 (with the knowledge of only the 3 FIQs in the $z < 0.5$ sample), we have argued that, if the variability and the core prominence is due to relativistic boosting, it is unlikely that those quasars are boosted radio-loud cores: at a given optical luminosity their allegedly boosted radio-cores are much weaker than the usual distribution of flat-spectrum radio quasars and as bright or even weaker than the cores of (unboosted) lobe-dominated quasars. Their total flux is also much lower than the total flux of radio-loud quasars, demonstrating that – like radio weak quasars – they lack anything similar to the radio lobes expected for radio-loud quasar. Hence, the only parent population they could have been boosted from are the radio-weak quasars. As shown in FMB89 the relative number of FIQs and their offset from the parent population is consistent with moderate Lorentzfactors of 3-5. An interesting test for the radio-weak blazar hypothesis for the FIQ will be VLBI observations and an investigation of their host galaxies – one would expect to find at least a few of them in spiral host galaxies, as opposed to radio-loud host galaxies which are exclusively in ellipticals.

3.4 Modelling the UV/radio distribution

The fact that we find such good correlations between the UV-bump and the radio luminosities also tells us a lot. Especially for the radio-weak quasars it shows clearly that the nuclear and the *extended* radio emission is AGN related. It would be very difficult to find an argument that the extended emission is produced by starbursts and explain the tight UV/radio correlation unless one is willing to postulate that the UV itself is produced by a starburst (as Terlevich et al. 1992). The total radio emission of the undisturbed, lobe-dominated radio-loud quasars, which is clearly jet-related, scales with the UV-bump as well, which indeed suggests a direct link between the radio-jet producing mechanism and the UV source.

We can now use the jet-disk model derived in Sec. 2 and compare it to the UV/radio correlation for the cores. Because we have carefully calibrated the line emission and the continuum fluxes and scaled them to the UV-bump luminosity, we are able to apply an actual physical model with absolute numbers to the distribution and hence can apply the mass and energy conservation laws to it.

To simplify the discussion, we will use only the most efficient model, where the internal energy is comparable to the kinetic energy and dominated by the magnetic field and relativistic particles. If we would start with a normal plasma jet, where the number of particles is limited by the mass conservation, and assume that all electrons are accelerated from the thermal pool ($\gamma_{\rm e} \sim 1$) into a powerlaw distribution, we find that we can well explain the radio luminosity of

Fig. 2. The same as Fig. 1 (CSS are not explicitly marked) but now the radio core flux is plotted. The shaded bands represent the radio-loud and radio-weak jet model where the width is determined by relativistic boosting. The dashed line represents sources at the boosting cone (inclination $1/\gamma$) and the solid line represents $0°$ inclination – corresponding to the maximum possible flux. The position of flat-spectrum and steep-spectrum sources and the radio-loud/radio-weak separation can be naturally accounted for with the coupled jet-disk model plus boosting.

the radio-weak quasars (Fig. 2, lower band), however, fail to explain the radio-loud quasars by a large margin if we demand $2q_{\mathrm{j/l}} < 1$. The reason for this is that in such a model the total energy of the electrons is still just a small fraction of the total energy dominated by the kinetic energy of the ions ("protonic model"), and most of the electrons are found at low energies where they do not contribute to the radio flux. To bring the electrons in equipartition, one either has to create additional pairs (100 times more then electrons) or inject them at a high energy where γ_{e} is of the order 100 ("electronic model"). Such models are the only ones, which are capable of explaining the UV/radio correlation for radio-loud quasar cores and they do require the 'total equipartition' mentioned in Section 2.

Interestingly, related energetical arguments earlier have led the editor of this book to speculate that high electron Lorentz factors must be present in radio jets (Kundt & Gopal-Krishna 1980). He interpreted this as evidence for ultrarelativistic bulk Lorentz factors, but as demonstrated in Fig. 2 the spread of radio core luminosities in jets (due to the anisotropy of relativistic boosting) is too narrow for such high bulk Lorentz factors and therefore those Lorentz factors must indicate internal, random motions of the electrons.

In order to reproduce the whole distribution of the radio cores, with the two equipartition models (electronic and protonic), we have to specify only two parameters: the jet-disk ratio $q_{\rm j/l}$ which we assume to be constant, and the proper velocity of jet for which we make the powerlaw Ansatz $\gamma_{\rm j}\beta_{\rm j} = 6((2/6)^{1/0.15}+L_{46})^{0.15}$. This allows a moderate increase of the jet velocity with power, where the typical quasar Lorentzfactor is $\gamma_{\rm j}\sim 6$ at $L_{46}=1$, but never becomes subrelativistic, i.e. smaller than $\gamma_{\rm j}\sim 2$. In Fig. 2 the two equipartition models are shown, depicting the regions within the boosting cone (dashed and solid line) and the unboosted population (shaded band); the jet/disk parameter used here is $2q_{\rm j/l}=0.3$ (two-sided jet).

Many conclusions can be drawn from this simple kind of analysis:

a) The Lorentzfactors have moderate values between 5-10, and there is no evidence for *stationary bulk* Lorentzfactors far in excess of 10 in quasars. Those sources – if seen face on – should have a radio/UV ratio much higher than seen in any of the sources in our sample.
b) Radio-loud sources are utmost efficient jets, and the differences between radio-loud and radio-weak sources are remarkably close to the difference between two natural stages of the electron distribution: one starting at thermal energies, the other shifted up in energy-space until equipartition is reached.
c) The radio jets have powers comparable to the disk luminosity, hence they must be produced in the very inner parts of the disk close to the black hole where the bulk of the gravitational energy is released.
d) The magnetic flux in the jet is much higher than the maximum possible radial magnetic flux in an accretion disk and hence the magnetic field for the jet must be produced locally at the footpoint and because of the high efficiency must be related somehow to the dissipation process in the disk (FB95).

4. Unified unification

4.1 The void of FR I quasars

There is another very interesting observation to be made in Figure 1. While the radio-quiet quasars spread out over the whole luminosity interval from $10^{44}-10^{48}$ erg/sec, radio-loud quasars are predominantly found in the range $L>10^{46}$ erg/sec, and none is below $L\sim 2\cdot 10^{45}$ erg/sec. One may argue that at the lower luminosities, the larger elliptical host galaxies become visible and therefore the sources are not classified as quasars, however, this falls short of explaining the void over 2 orders of magnitude. The alternative explanation is that in fact below a critical power, radio-loud quasars lose their typical quasar characteristics, i.e. the broad (and narrow) emission lines and the UV bump. A hint why this may be so comes from the radio morphological data we have for the PG quasars: all radio-loud sources are either of FR II type or compact, none has a typical FR I structure, and indeed it is part of the radio-astronomers folklore that FR I radio sources never show up as quasars. *Consequently, we can identify the void of radio-loud quasars below a certain optical luminosity with the FR II (high-power) to FR I (low-power) transition.* This link between transition of radio morphology and disappearence of optical emission is difficult to understand, especially as the emission line properties of radio-weak quasars – which are almost identical to those of radio-loud quasars – do not show any change at this critical power. Thus just a change (or disappearance) of the accretion disk with decreasing power seems unlikely. A change of the engine would also violate the simplicity of our Ansatz and therefore is not the preferred option here.

4.2 The closing torus

The question now is whether we can explain the behaviour of the radio-loud sources qualitatively without having to postulate different central engines. A minor modification to the unified scheme may indeed do this job: if the opening angle of the obscuring torus is not constant but power-dependent, the torus could approach the jet opening angle at low powers. In this case the central engine would be obscured for almost all aspect angles, and the interaction between the jet and the torus could start the disruption of the low-power jet and initiate its morphological transition (Falcke, Gopal-Krishna, & Biermann 1995).

4.3 Observational consequences

Consequently we would not expect to see broad emission lines from a FR I type radio source as the broad-line region is expected to be inside the 1-100 pc scale torus and be completely obscured. If the opening angle is smaller than the boosting cone, even for boosted FR Is (i.e. BL Lacs) most of the emission line region would be obscured. In fact, one would have to wonder if broad emission line clouds could survive at all in the narrow funnel of the torus if it extends down to the smallest scales. The narrow lines would also be strongly suppressed as the escaping ionizing continuum that produces the NLR region itself is suppresssed. The same is true for broad lines in polarized (scattered) light: as there is not much optical light escaping from the nucleus there will also not be much light that could be scattered.

The best wavelength regime to test the "closing torus" scenario would therefore be the IR where most of the energy of the central source should be re-emitted, predominantly at 10-20μm. The FR I should therefore have an IR output comparable to FRII radio galaxies and quasars scaled to the same engine power. As already in FR II galaxies and quasars, more than half of the energy is absorbed, the *relative* increase in the IR luminosity for FR I, where almost everything is absorbed, is less than a factor two and difficult to detect. However, because of the different shapes of the tori, the IR spectrum itself (e.g. 10μm silicate feature) might be different (see Pier & Krolik 1992). Also NIR spectroscopy might reveal the presence of a quasar engine in FR I radio galaxies; a first pilot study is currently on the way.

Another observational effect concerns the ratio between quasars and radio galaxies in low-radio-frequency selected (orientation independent) samples. This ratio should not be constant but depend on the power of the central engine as it reflects the width of the torus opening. Such a powerdependence is indeed observed (and often used as an argument against the quasar/galaxy unification; Lawrence 1991; Singal 1993).

4.4 Making the jet radio-loud

The fact that the jet may interact with the torus opens the field for many interesting speculations and future studies. If we imagine a powerful, magnetized, relativistic jet scraping along the inner parts of a dense torus (or a cloud therein, or a cloud blown off its surface) we may anticipate the formation of a violent shear layer between jet and the external medium. The interaction might induce highly oblique shocks where particles are accelerated and thus would make the jet radio loud. If the shear-layer is very thin, magnetized and dense, collisions of the ions, carried by the jet at relativisitic speeds, with the external matter would lead to hadronic cascades and consequently to the production of gamma rays and to the injection of pairs at $\gtrsim 35$ MeV – this could also make the jet radio-loud.

In this context it is interesting to note that AGN jets cannot start as radio-loud jets. The synchrotron losses and the inverse Compton losses of the relativistic particles with the UV photons from the disk would be catastrophic and lead to a complete dissipation of the relativistic electrons with high Lorentz factors in its inner parts. A simple extrapolation of the radio emission to the black hole scale would also predict a radio luminosity in excess of the jet power. The typical scale where the losses become less severe and the electron injection can happen is $z \gtrsim 10^{16-17}$ cm (FB95). This is close to the scale often quoted for the production of gamma rays and the scale for the BLR. One starts to wonder whether gamma-ray emission, electron injection and jet torus or jet/BLR interaction have something to do with each other.

4.5 Torus and host galaxy

In the whole discussion we have ignored the nature of the torus and its origin and why it should be powerdependent. None of these questions can be readily answered. The torus may be just a very thick accretion disk with a steep funnel, or it may be composed of molecular clouds in turbulent motion. The powerdependence of its opening might be due to heating and depletion of its inner parts by the central engine or due to the jet itself that drills through a more or less sphercial dust distribution and carries matter outwards, thereby opening the "torus".

In any case a very high (gas, magnetic, or turbulent) pressure is needed to maintain the thickness of the torus. Besides the electron injection discussed above, interaction of the jet with the torus itself, or with winds or clouds produced by it, may therefore also have a confining effect at the inner torus scale (sub-pc to pc). A jet without such a closing torus and without the jet/torus interaction would neither be well collimated nor have the efficient injection of electrons/pairs to make it radio-loud. *Hence it is in principle possible to attribute the radio-loud/radio-quiet dichotomy to different environments at the pc scale rather than to differences in the engine itself.*

The advantage of this concept is that it is easier to relate the pc scale environment rather than the engine properties to the host galaxy. It was proposed that the merging of galaxies may lead to a spin-up of the central black hole by black hole merger during the creation of an elliptical galaxy (Wilson & Colbert 1995). However, it is by no means clear why spiral galaxies should not have a rotating black hole ab initio. Nevertheless, the idea of mergers being a necessary prerequisite for the production of a radio-loud jet is quite tempting and supported by observations (e.g. Heckman et al. 1986). And indeed it seems unavoidable that such a merger sooner or later leads to the formation of a single black hole. There is, however, a critical separation between the two merging holes – again at the pc scale – where neither gravitational friction nor gravitational radiation is very efficient (Begelman, Blandford, Rees 1980), and the binary may stay there for quite a while. So, merging may lead to black hole coalescence, but it definitively will also change the pc-scale structures of the stars and the dust in the central bulge in a way which will be very different from those in spiral galaxies!

5. Starved and stellar-mass black holes

5.1 Sgr A* and its siblings

An interesting consequence of our approach is that it is to first order independent of the scale. If jets and disks are symbiotic features, this may apply to almost any kind of accretion disk with a compact central mass. The equations in Sec. 2 do not depend on the mass of the central object but mainly on the mass accretion rate (i.e. the disk luminosity) and consequently we can use the same scheme for stellar-mass black holes and for the starved black holes in inactive galactic nuclei such as in our own Galaxy. In fact, the jet/disk symbiosis was initially developed to explain the Galactic Center source Sgr A* (Falcke et al. 1993a&b; Falcke 1996a&b) and the jet/disk model still remains a viable explanation for this compact source. Also the radio core of other weakly active galaxies like M81 and M31 seem to follow the same rules (see Falcke 1994, Figure 8.1).

5.2 Galactic jet sources

The sources which received most attention recently are the galactic jet sources associated with either neutron stars or black hole candidates. Two of those sources show apparent superluminal motion indicating relativistic speeds, and they have properties similar to extragalactic jets (Mirabel & Rodriguez 1994; Hjellming & Rupen 1995). Besides those sources, we also know a few other sources in the Galaxy (1E1740-2942, SS433, GRS 1758-258) which show clear jets but without superluminal motion yet detected, and a few x-ray binaries do show flat spectrum radio cores which might be related to a jet. To compare the radio cores of all these sources with their disk luminosity, one has to use x-ray data because the disk spectrum of low-mass black holes is shifted to higher energies. In Fig. 3 the galactic jet sources are shown in a diagram similar to Fig. 2 but extending now down to very low luminosities (Falcke & Biermann 1996). As one can see, no change of the basic parameters is necessary to roughly predict the range of radio fluxes expected for these sources at a luminosity which is 6-10 orders of magnitude lower than in the supermassive AGN black holes. There is even a hint for a dichotomy between radio-loud and radio-weak sources among the galactic jets, but the statistics are not yet good enough. The fact that those equations and the formulation of the symbiosis principle that implied the presence and the luminosity of the galactic superluminal jet sources (FB95; Falcke 1994) were suggested *before* the discovery of those sources, demonstrates the predictive power of this principle — and there is yet a lot of parameter space in Fig. 3 to be filled.

Fig. 3. The same model and data as in Fig. 2 for quasars but now extended to lower powers where galactic jet sources are found. Here the disk luminosity corresponds is interpreted as the x-ray luminosity. Big stars represent confirmed jet sources, while small stars represent x-ray binaries. The big black dots are Sgr A* and M31*.

6. Summary

This work could be summarized by stating that at present it is *not possible* to show observationally that the central engines in AGN are essentially different (i.e. on a scale of 10-100 $R_{\rm g}$). Postulating that jets and disks around compact objects are symbiotic and universal features is sufficient to account for most of the observed effects and allows several interesting conclusions:

- The jet/disk coupling explains the UV/radio correlation for quasars and the x-ray/radio flux of stellar-mass black holes.
- Radio-loud jets are utmost efficient and have total powers comparable to the disk luminosities.
- The distribution of flat- and steep-spectrum quasars within the UV/radio correlation reflects relativistic boosting with $\gamma_{\rm j} \sim 5$, and a population of flatspectrum radio-intermediate quasars (FIQ) suggests the presence of relativistic jets in radio-weak quasars.
- The pc-scale environment ("the torus") may change the jet properties drastically. For example, a closing torus in radio-loud galaxies may explain the transition from FR II jets to FR I jets and the weakness of emission lines in FR I and BL Lacs. The jet/torus interaction may in principle also help to make a jet radio-loud.
- There is no fundamental difference in the parameters between jets from stellar-mass und supermassive black holes.

The fact that stellar-mass black holes and AGN can be described with the same simple jet/disk model (Fig. 3) suggests that there is a universal correlation between radio emision and disk luminosity that spans the whole luminosity range from a few hundred solar luminosities up to several $10^{14}L_{\odot}$, and hence there may be quite a few other sources (e.g. Seyfert galaxies and nearby galactic nuclei) that follow the same trend but have not yet been discussed in this respect.

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