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The jet/disk symbiosis III.

What the radio cores in GRS 1915+105, NGC 4258, M81, and Sgr A tell us about accreting black holes

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Abstract. We have derived simplified equations for a freely expanding, pressure driven jet model as a function of jet power and applied it successfully to the radio cores in the black hole candidates GRS 1915+105, NGC 4258, and M81 which are observationally well defined systems, and to Sgr A*. By using equipartition assumptions, the model has virtually no free parameters and can explain all sources by just scaling the jet power. In GRS 1915+105 it also naturally explains the jet velocity and the radio time delay. The jet powers we derive for the radio cores of the first three sources are comparable to their accretion disk luminosities, providing further evidence for the existence of symbiotic jet/disk systems and a common engine mechanism also in low-luminosity AGN and stellar mass black holes. With the exception of Sgr A* an advection dominated accretion flow (ADAF) does not seem to be necessary to explain any of the radio cores which span a large range in luminosity and size, as well as in black hole masses and accretion rate—from Eddington to extreme sub-Eddington. We suggest, however, that the jet model can be used to derive minimum accretion rates and thus find that Sgr A* seems to be truly radiatively deficient—even in a starved black hole model—and that a combination of jet and ADAF model may be one possible solution.

Key words: stars: GRS 1915+105 – galaxies: active – galaxies: jets – galaxies: nuclei – galaxies: individual (NGC 4258) – accretion

1. Introduction

Early on in the discussion about the existence of black holes Lynden-Bell & Rees (1971) suggested that they would be accompanied by compact radio nuclei, detectable by Very Long Baseline Interferometry (VLBI), and predicted such a source for the Galactic Center. Indeed, this source (Sgr A*) was then discovered by Balick & Brown (1974) and it became clear in later years that compact radio cores are indeed good evidence for the existence of active galactic nuclei (AGN) most likely powered by black holes. For luminous radio galaxies and radio-loud quasars the basic nature of these compact radio nuclei has been clarified in the meantime through extensive and detailed VLBI observations (see Zensus 1997 for a review) as being the inner regions of relativistic jets emanating from the nucleus.

Despite this progress, a number of important questions remain when looking back at the initial discussion. First of all, it is unclear whether there indeed is a direct link between compact radio cores and AGN, i.e. whether compact radio cores and jets are just an accidental by-product of black hole activity or a necessary consequence. Secondly, for the lesser studied, low-luminosity AGN the jet nature of compact radio nuclei has not yet been established beyond any doubt, leaving the question open whether in fact a compact radio core in a low-luminosity AGN (LLAGN) is the same as in a high-luminosity AGN, i.e. a quasar.

The latter was exactly the claim we made in an earlier paper (Falcke & Biermann 1995) where we proposed that accretion disks and jets form symbiotic systems and proposed a scaling law which connects high-power and lower-power accretion disks and their associated radio jets (cores). The scaling law was based on the assumption of an equipartition between the energy released and radiated away through dissipation processes in the accretion disk and the power put into the formation of magnetically driven radio jets.

The question whether this scaling law holds all the way down to low-luminosity AGN, as claimed in Falcke & Biermann (1996), also has some very interesting implication for the current discussion of accretion flows. Since

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the early papers on the observational appearance of black holes (e.g. Shakura & Sunyaev 1973) it was assumed that luminous, thermal emission at optical, ultra-violet (UV), or X-ray wavelengths was the primary sign for the presence of an accreting black hole. It was argued that any matter falling onto the black hole would likely form an accretion disk, if there was any residual angular momentum, and hence would need to dissipate its potential energy into heat by viscous processes allowing it to transport angular momentum outwards while matter is falling inwards (α-disk). This idea was used successfully to explain the "big blue bump" in quasars (e.g. Sun & Malkan 1998).

However, the view that the α-disk can be extended to much lower powers has been challenged (Narayan & Yi 1994, 1995a&b) and it was argued that accretion disks will turn into advection dominated accretion flows (ADAFs) if the accretion rate onto the black hole is sufficiently sub-Eddington. Narayan et al. (1995 & 1998; see also Rees 1982 and Melia 1994) applied this to the Galactic Center, trying to explain the compact radio source Sgr A* and its faintness at other wavelengths, and Lasota et al. (1996) used the ADAF model to explain the broad-band spectrum of the nearby LLAGN and LINER galaxy NGC 4258 which is famous for its megamaser emission from a molecular disk (Miyoshi et al. 1995). An integral part of these ADAF models is the prediction of very compact radio emission associated with the innermost part of the accretion flow, providing an alternative explanation to the jet model for compact radio nuclei in LLAGN. While initially the predicted, highly inverted radio spectra of the ADAF model, did not fit the observed characteristics of these radio cores very well, Mahadevan (1998) presented a more recent version of this model that was at least able to account for the correct radio spectrum of Sgr A*[1]. Still, Di Matteo et al. (1998) found a number of serious constraints for ADAF models—at least for compact radio nuclei in elliptical galaxies.

Hence, the question now is whether indeed the radio emission from compact nuclei in sub-Eddington accretion systems can be used as an argument for the existence and necessity of ADAFs, or whether they are equally well, or even better explained, in a scaled down AGN jet model. The latter will be tested in this paper: firstly, we will use the jet/disk-symbiosis model of Falcke & Biermann (1995) in its most recent version (Falcke 1996b) and present simplified approximate solutions that can be applied easily. Secondly, we will apply those solutions to some specific sources which are of particular interest in this discussion and are observationally well constrained in their parameters. Finally we will discuss our results within the context of the jet/disk-symbiosis model and their implications for ADAFs.

[1] Interestingly, the proposed process (pion decay in pp-collisions) had also been proposed and used within the jet model for the Galactic Center (Falcke 1996a)

2. The jet/disk-symbiosis model

2.1. Basics

The model by Falcke & Biermann (1995) was derived from a simple Blandford & Königl (1979) model which calculates the synchrotron emission of a relativistic, conical jet as a function of jet power $Q_{\rm jet}$ (here: of two cones) parametrized by the accretion disk luminosity $L_{\rm disk}$, such that $Q_{\rm jet} = q_{\rm j/l} L_{\rm disk}$. Here we will make use of this parametrization only to recapitulate our earlier results and later express the simplified equations in terms of the jet power alone. In the end we will therefore be able derive the parameter $q_{\rm j/l}$ without making any ab-initio assumptions about its value.

The maximally efficient model assumes equipartition between magnetic field and particles and between internal and kinetic energy ($\beta_{\rm s} = \sqrt{(\Gamma-1)/(\Gamma+1)} \sim 0.4$). In Falcke (1996b) we added a self-consistent description of the velocity field: the jet was considered to be a fully relativistic electron/proton plasma with a turbulent magnetic field treated as a photon gas leaving a nozzle and freely expanding into the vacuum (this is in contrast to large scale jet models which assume pressure equilibrium and confining cocoons). The longitudinal pressure gradient then leads to a modest, yet significant acceleration along the z-axis of the jet in the asymptotic (i.e. observable) regime given by the equation for the jet proper velocity $\gamma_{\rm j}\beta_{\rm j}$

$$\left(\frac{\left(\frac{\Gamma+\xi}{\Gamma-1}\right)(\gamma_{\rm j}\beta_{\rm j})^2-\Gamma}{\gamma_{\rm j}\beta_{\rm j}}\right)\frac{\partial\gamma_{\rm j}\beta_{\rm j}}{\partial z}=\frac{2}{z} \tag{1}$$

with $\xi = (\gamma_{\rm j}\beta_{\rm j}/(\Gamma(\Gamma-1)/(\Gamma+1)))^{1-\Gamma}$ and an adiabatic index $\Gamma = 4/3$ (Falcke 1996b).

This model assumes that there is no additional acceleration beyond the nozzle and therefore just gives a lower limit to the terminal jet speed of order $\gamma_{\rm jet} = 2-3$ which seems to be just enough for some low-power nuclei. This will of course fail for powerful quasar jets since they exhibit significantly faster motion. We also point out that this does not make any assumption on the process of jet formation itself which is here treated as a "black box" of linear dimension $Z_{\rm nozz}$ so that $z = Z/Z_{\rm nozz}$, where Z is the distance from the black hole.

The radio spectrum of such a pressure driven jet (which is no longer perfectly conical) can then be calculated assuming energy conservation along the jet when assuming a certain energy distribution of the relativistic electrons as described in more detail in Falcke (1996b). For simplicity we assume that a fraction $x_{\rm e}$ of the electrons gets accelerated up to an initial characteristic energy of $\gamma_{\rm e} m_{\rm e} c^2$ (or possibly produced near this energy by $\pi^{\pm}$-decay, e.g. Biermann et al. 1995). While the existence of quasi-monoenergetic electron distributions has been claimed for LLAGN (Duschl & Lesch 1994; Reuter et al. 1996), this choice here was made mainly to account for the possibility of a low-energy cut-off/break in the electron distribution (Celotti & Fabian 1993; Falcke & Biermann 1995). Since in almost all cases $\gamma_{\rm e}$ will have to be such that the characteristic frequency $\nu_{\rm c}$ is close to the self-absorption frequency $\nu_{\rm ssa}$, all the results obtained here will also be roughly valid for a more realistic power-law distribution with low-energy break at $\gamma_{\rm e}$. On the other hand it can also not be excluded that indeed electrons in radio cores start out with a very narrow energy distribution when they are injected and only along the way get accelerated into a power-law distribution.

2.2. Simplified equations

Using all the basic premises above, one arrives at a set of equations for the expected radio spectrum and typical size scale of a radio core for a given accretion disk luminosity (or jet power), inclination angle and electron energy, given as Eqs. (8-12) in Falcke (1996b) for the case of M81*, which we reproduce here (using the parameters exactly as specified in that paper). The characteristic scale $z_{\rm c}$ of the radio core is

$$z_{\rm c} = (z_{\rm c,0}/\sin i)(\mu_{\rm p/e}x_{\rm e})^{-2\xi}\,(q_{0.5}L_{41.5})^{\xi/2}\,z_{13.7}^{1-\xi}\nu_{10.3}^{-\xi} \qquad (2)$$

where the parameters are $z_{13.7} = z_0/3\,{\rm AU}$, $\nu_{10.3} = \nu/22$ GHz, $\xi = (0.99, 0.95, 0.9, 0.89, 0.88)$ and $z_{\rm c,0}$ =(500, 1200,1100, 900, 700) AU for $i = (5°, 20°, 40°, 60°, 80°)$, while the total spectrum of the jet is given by

$$\begin{aligned}
S_\nu &= 745\,{\rm mJy}(q_{0.5}L_{41.5})^{1.46}\mu_{\rm p/e}^{.17}x_{\rm e}^{1.17}z_{13.7}^{0.08}\nu_{10.3}^{0.08}\\
&\quad -337\,{\rm mJy}(q_{0.5}L_{41.5})^{1.54}\mu_{\rm p/e}^{.92}x_{\rm e}^{2.1}z_{13.7}^{0.08}\nu_{10.3}^{0.08}, \qquad (3)\\
S_\nu &= 247\,{\rm mJy}(q_{0.5}L_{41.5})^{1.42}\mu_{\rm p/e}^{.33}x_{\rm e}^{1.33}z_{13.7}^{0.16}\nu_{10.3}^{0.16}\\
&\quad -143\,{\rm mJy}(q_{0.5}L_{41.5})^{1.48}\mu_{\rm p/e}^{.85}x_{\rm e}^{1.95}z_{13.7}^{0.15}\nu_{10.3}^{0.15}, \qquad (4)\\
S_\nu &= 106\,{\rm mJy}(q_{0.5}L_{41.5})^{1.40}\mu_{\rm p/e}^{.40}x_{\rm e}^{1.40}z_{13.7}^{0.20}\nu_{10.3}^{0.20}\\
&\quad -71\,{\rm mJy}(q_{0.5}L_{41.5})^{1.45}\mu_{\rm p/e}^{.81}x_{\rm e}^{1.89}z_{13.7}^{0.19}\nu_{10.3}^{0.19}, \qquad (5)
\end{aligned}$$

for $D = 3.25$ Mpc, and $i = (20°, 40°, 60°)$ respectively.

Unfortunately, these equations are not easy to handle since the power-law indices are a function of the inclination angle. We therefore derive here an approximate formula for the spectra and sizes predicted by such a model.

We note here once more that Eq. 3 has two inherent constraints. First of all, by definition $\mu_{\rm p/e}$ cannot be smaller than unity since it is defined as the ratio between the energy densities in protons and electrons plus one. For the sake of simplicity only, we will now ignore the relativistic proton content and set $\mu_{\rm p/e} = 1$, so that we can substitute the relativistic electron fraction $x_{\rm e}$ with

$$x_{\rm e} = m_{\rm p}/\left(4\Gamma m_{\rm e}\gamma_{\rm e}\right) = 344/\gamma_{\rm e}. \qquad (6)$$

Secondly, one cannot increase $\gamma_{\rm e}$ indefinitely since at some point the flux would become negative, i.e. the jet would become completely self-absorbed and the simplifications would break down. Moreover, the equations are difficult to handle because of this sum, since for large changes in $Q_{\rm jet}$ the sum also would become negative. Hence,, we formally introduce an arbitrary scaling relation

$$\gamma_{\rm e} = \gamma_{\rm e,0}\left(\frac{Q_{\rm jet}}{10^{39}{\rm erg/sec}}\right)^{0.09} \qquad (7)$$

which allows us to simplify the equations further. The physical meaning is that electrons are pushed to somewhat higher energy with increasing $Q_{\rm jet}$ to keep them in the optically thin part. A mechanism which indeed could lead to such an effect is the 'synchrotron boiler' (Ghisellini et al. 1988) that describes the evolution of low-energy electrons in a self-absorbed system, but it is not clear whether this formally introduced relation here has any significance in the real world and therefore we will ignore it in the discussion of our results.

To further simplify the equations we have rounded the exponents typically to the 2nd digit after the decimal and factorized the equations. Even for the most strongly varying parameters, like $L_{\rm disk}$ which can vary over 6 orders of magnitude, the resulting error will be only some ten percent. Moreover, the exponents in the equations, which are a function of the inclination angle i of the jet, were fitted by 2nd and 3rd order polynomials in i to an accuracy of much better than a few percent over a large range of angles.

All these simplifications lead to the following expressions for the observed flux density and angular size of a radio core observed at a frequency ν as a function of jet power. For a source at a distance D, with black hole mass $M_\bullet$, size of nozzle region $Z_{\rm nozz}$ (in $R_{\rm g} = GM_\bullet/c^2$), jet power $Q_{\rm jet}$, inclination angle i, and characteristic electron Lorentz factor $\gamma_{\rm e}$ (see Eq. 7) the observed flux density spectrum is given as

$$\begin{aligned}
S_\nu &= 10^{2.06\cdot\xi_0}\ {\rm m}Jy\ \left(\frac{Q_{\rm jet}}{10^{39}{\rm erg/sec}}\right)^{1.27\cdot\xi_1}\\
&\cdot\left(\frac{D}{10{\rm kpc}}\right)^{-2}\left(\frac{\nu}{8.5{\rm GHz}}\right)^{0.20\cdot\xi_2}\left(\frac{M_\bullet}{33M_\odot}\frac{Z_{\rm nozz}}{10R_{\rm g}}\right)^{0.20\cdot\xi_2}\\
&\cdot\left(3.9\cdot\xi_3\left(\frac{\gamma_{\rm e,0}}{200}\right)^{-1.4\cdot\xi_4} - 2.9\cdot\xi_5\left(\frac{\gamma_{\rm e,0}}{200}\right)^{-1.89\cdot\xi_6}\right), \qquad (8)
\end{aligned}$$

with the correction factors ξ_{0-6} depending on the inclination angle i (in radians):

$$\begin{aligned}
\xi_0 &= 2.38 - 1.90\,i + 0.520\,i^2 \qquad (9)\\
\xi_1 &= 1.12 - 0.19\,i + 0.067\,i^2 \qquad (10)\\
\xi_2 &= -0.155 + 1.79\,i - 0.634\,i^2 \qquad (11)\\
\xi_3 &= 0.33 + 0.60\,i + 0.045\,i^2 \qquad (12)\\
\xi_4 &= 0.68 + 0.50\,i - 0.177\,i^2 \qquad (13)
\end{aligned}$$

$$\xi_5 = 0.09 + 0.80\,i + 0.103\,i^2 \quad (14)$$
$$\xi_6 = 1.19 - 0.29\,i + 0.101\,i^2. \quad (15)$$

Likewise, the characteristic angular size scale of the emission region is given by

$$\Phi_{\rm jet} = 1.36 \cdot \chi_0 \,\text{mas}\,\sin i \cdot \left(\frac{\gamma_{\rm e,0}}{200}\right)^{1.77\cdot\chi_1} \left(\frac{D}{10{\rm kpc}}\right)^{-1} \left(\frac{\nu}{8.5{\rm GHz}}\right)^{-0.89\cdot\chi_1} \cdot \left(\frac{Q_{\rm jet}}{10^{39}{\rm erg/sec}}\right)^{0.60\cdot\chi_1} \left(\frac{M_\bullet}{33M_\odot}\,\frac{Z_{\rm nozz}}{10R_{\rm g}}\right)^{0.11\cdot\chi_2}, \quad (16)$$

with the correction factors

$$\chi_0 = 4.01 - 5.65\,i + 3.40\,i^2 - 0.76\,i^3 \quad (17)$$
$$\chi_1 = 1.16 - 0.34\,i + 0.24\,i^2 - 0.059\,i^3 \quad (18)$$
$$\chi_2 = -0.238 + 2.63\,i - 1.85\,i^2 + 0.459\,i^3, \quad (19)$$

where again the inclination angle i is in radians. We point out that in this model the characteristic size scale of the core region is actually equivalent to the offset of the radio core center from the dynamical center. This does not exclude the existence of emission in components further down the jet, which might be caused by shocks or other processes.

The equations are scaled to the typical values for Galactic jet sources like GRS1915+105 and the correction factors are normalized to an inclination angle of 1 rad ($\sim 57°$). We note that the approximations fail at small inclination angles where the accretion disk is seen face on and the jet points towards the observer (i.e. $i \lesssim 10°$). The benefits of these equations now are that they can be used to quickly compare observed radio core properties with the model predictions, especially since we have reduced the number of free parameters to the absolute minimum.

3. Application to individual sources

Application of these simplified equations to real radio cores is straight forward, the basic input parameters being the jet power, the characteristic electron energy, the inclination to the line of sight, the observed frequency, the distance, the black hole mass, and the relative size of the nozzle region. The latter two enter only weakly and hence need to be known only to an order of magnitude.

A few systems are so well studied that most of these parameters (especially i, D, & $M_\bullet$) can be fixed with some confidence and where size and flux of their cores at a certain frequency are well known through VLBI observations. Even though this may be a subjective criterion, we believe that the radio cores in M81, NGC 4258, and GRS 1915+105 are, for various reasons, perhaps the best studied and best constrained examples of low-power radio cores. Following the convention in Falcke (1996b) and Melia (1992) and in analogy to Sgr A*, we will identify the radio cores in these sources by adding an asterisks to their host galaxy or source name to clearly distinguish them from their hosts.

We have listed the sources and their parameters in Table 1. The observed quantities we have used as input parameters for the model are given in Columns 2-7. Since in all cases, except Sgr A*, we have only two unknowns left (jet power and characteristic electron energy) to describe the two observed quantities of the radio cores (flux and size) we were able to solve the model equations for each source completely and determine $Q_{\rm jet}$ and $\gamma_{\rm e}$ directly from the observations. These results and the predicted spectral indices for the radio spectrum are given in the three rightmost columns of Table 1. For comparison with the jet power, we also listed the accretion disk luminosity of each system in Column 8. In the following we will briefly discuss the data and the modelling of each source.

3.1. NGC 4258

The VLBI observations of megamaser emission has led to the detection of a molecular disk in NGC 4258 (Miyoshi et al. 1995) which can be used to determine the inclination angle $i = 82°$ of the system, the black hole mass $M_\bullet = 3.5 \cdot 10^7 M_\odot$, and the distance $D = 7.3 \pm 0.3$ Mpc (Herrnstein et al. 1997a) almost directly from the observations. The variable central VLA radio core (Turner & Ho 1994), here called NGC 4258*, has a flux of roughly 3 mJy and was interpreted by Lasota et al. (1996) as emission from an ADAF while Falcke (1997) suggested a scaled down AGN jet origin. The latter picture was confirmed by Herrnstein et al. (1997b&1998) who discovered a nuclear jet in NGC 4258 offset by 0.35 to 0.46 mas from the dynamical center. Herrnstein et al. (1996) suggested that this offset could be interpreted within the framework of the Blandford & Königl (1979) model as being due to self-absorption in the inner jet cone. The search for radio emission directly at the dynamical center remained unsuccessful (Herrnstein et al. 1998) and required a revision of the Lasota et al. (1996) ADAF model (Gammie et al. 1998).

For our purposes NGC 4258* is an ideal system because all crucial parameters, especially the inclination angle, seem to be fixed. Using an average radio flux of 3 mJy at 22 GHz and the offset of the core from the dynamical center as the characteristic size scale of the system we find a jet power of $10^{41.7}$ for the nuclear jet, a characteristic electron Lorentz factor of ~ 630, and predict an average spectral index $\alpha = 0.22$ ($S_\nu \propto \nu^\alpha$). The jet-power of the nuclear jet is consistent with the large scale emission-line jet in NGC 4258, since its kinetic power is also of the order 10^{42} erg/sec — as derived from the mass ($2 \cdot 10^6 M_\odot$) and velocity ($\sim$ 2000km/sec) of the emission-line gas (Cecil et al. 1995). Moreover, this is also in line with the estimated nuclear accretion disk luminosity of $\sim 10^{42}$erg/sec

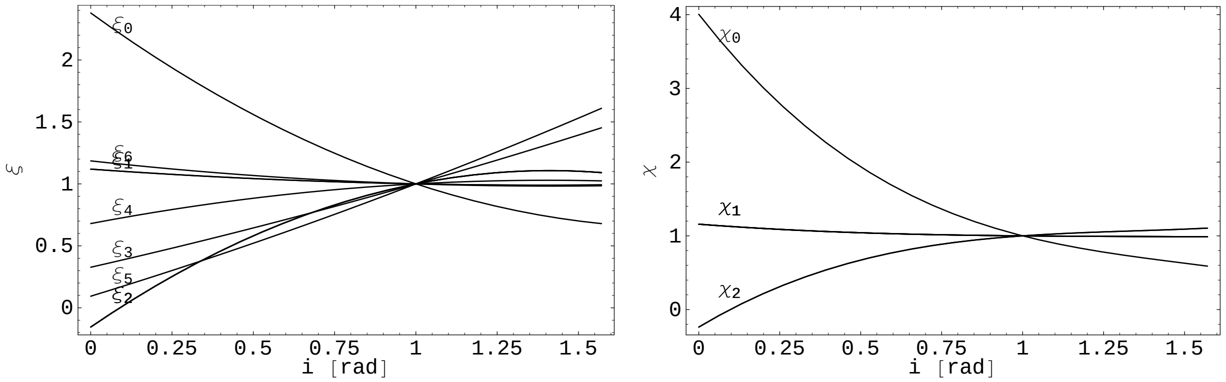

Fig. 1. Correction factors ξ and χ for the exponents and fore-factors in Eqs. 8 & 16 as a function of inclination angle i in radians, where $i = 0$ corresponds to face-on orientation. Note, however, that for $i \lesssim 10^\circ$ most approximations fail.

(Stüwe et al. 1992; Wilkes et al. 1995; see also discussions in Herrnstein et al. 1997 and Gammie et al. 1998). Hence, all the activity in NGC 4258 can be described in a consistent way by a low-luminosity jet/disk-system and an accretion rate of the order $10^{-4} M_\odot$/yr. One caveat exists, however, because the interpretation of the offset of the core from the dynamical center as the characteristic scale of the model (and not the self-absorption size which is smaller in this model) actually implies that also the core size is of similar order. If it were smaller, e.g. 0.1 mas, this would reduce the, compared to other sources, relatively high value for $\gamma_{\rm e}$ to around 200 without significantly reducing the required jet power. A difference between offset and actual core size would occur if the jet were collimated in the inner region more than assumed in our model (i.e. were narrower than the Mach cone).

3.2. GRS 1915+105

Mirabel & Rodriguez (1994) discovered a compact radio jet in GRS 1915+105 with apparent superluminal motions, for which they were able to determine the jet speed ($0.92c$) and the inclination angle ($\sim 70^\circ$) of the system. Moreover, in recent papers Fender et al. (1997), Pooley & Fender (1997), Mirabel et al. (1998) and Eikenberry et al. (1998) found an intriguing correlation between radio outbursts and X-ray flares and hence a symbiotic jet/disk-system as proposed in Falcke & Biermann (1995&1996) seems to be a good description for GRS 1915+105. The parameters $L_{\rm disk} \sim 10^{39}$erg/sec and $M_\bullet \sim 33 M_\odot$ are discussed in the literature (e.g. Mirabel et al. 1997; Morgan et al. 1997) for this source, but we point out that the mass determination is extremely uncertain, yet is also not really critical for the modelling.

Dhawan et al. (1998) observed the central radio core in a relatively quiescent phase finding an intrinsic source size of ~ 2 mas (major axis) at 15 GHz and fluxes around 40 mJy (flat spectrum). For these parameters the jet model gives a jet power of $10^{39.1}$ erg/sec and a $\gamma_{\rm e}$ of ~ 400. In addition, the predicted scaling of the core size ($\propto \nu^{-0.9}$) is consistent with the observed one (roughly $\propto \nu^{-1}$, taking out the scatter broadening). The observed time delay of ~ 4 min of outburst peaks between 3.5 and 2cm can be explained as the delay in time it takes for each outburst to reach the optically thin regime ($\tau \simeq 1$) at the angular distance $\Phi_{\rm s}$ where the outburst first becomes visible. For the parameters given here and in Table 1 we get[2] $\Phi_{\rm s} = 0.035$ mas and the time delay between 2 and 3.5 cm is predicted by the model to be of order 3 mins. The velocity of the jet in the model grows asymptotically as determined by Eq. 1 (see also Falcke 1996b), yielding $\beta = 0.92$ at $10^4 R_{\rm g}$ and $\beta = 0.96$ at the scale of a few mas, where the radio emission is coming from. Considering that Eq. 1 is a no-fit asymptotical description of the velocity field in the jet this is a reasonably good prediction. Clearly, the pressure gradient effect must be at work at least to some degree here. Mirabel & Rodriguez (1994) found tentatively that—in addition to their advance speed—the blobs may also expand with $0.2c$ at larger scales, thus perhaps finding direct evidence for a relativistic "sound speed" which is needed for the pressure gradient effect to be important. All in all the Falcke (1996b) model for M81* seems to give a remarkable good description of GRS 1915+105 as well and it confirms the basic Hjellming & Johnston (1988) picture for compact radio cores in stellar mass black hole candidates.

3.3. M81 and Sgr A**

Finally, for a consistency check, we will apply the model presented here also to M81* and Sgr A* for which we have discussed very similar jet-models and their parameters al-

[2] This is smaller than Φ where the spectrum should peak. In the light curve the actual peak of an outburst could appear somewhere between those scales if the duration of the outburst were smaller than the travel time between $\Phi_{\rm s}$ and Φ.

ready in earlier papers (Falcke, Mannheim, Biermann 1993 and Falcke 1996b) while adding a few recent results that have appeared in the literature.

For M81* Ebbers et al. (1998) and Bietenholz et al. (1998) presented some new measurements confirming that indeed it most likely has a core-jet structure. The average flux and size of M81* at 8.5 GHz was ~ 120 mJy and ~ 0.5 mas. Falcke (1996b) concluded that a range of inclinations between $30-40^\circ$ fitted the radio observations best and this was confirmed by the detection of a nuclear emission line disk in M81 with similar inclination (Devereux et al. 1997). The jet power derived from our model of M81* with these parameters is $10^{41.8}$ erg/sec and $\gamma_\mathrm{e}=250$. For comparison, Ho et al. (1996) give a bolometric nuclear luminosity for M81 of $10^{41.5}$ erg/sec.

For the Galactic Center radio core Sgr A* observational results now convincingly demonstrate the presence of a black hole of mass $2.5\cdot 10^6 M_\odot$ (Ghez et al. 1998; Eckart & Genzel 1996) while the exact nature of this source remains ambiguous. For the intrinsic size of Sgr A* at 43 GHz Bower & Backer (1998) give a 2σ value of ~ 0.5mas and in a later paper Lo et al. (1998) indeed claim this to be the intrinsic size together with an elongated source structure they find. Assuming an arbitrary inclination angle of 45° one can fit Sgr A* with a jet power of $10^{38.7}$ erg/sec and $\gamma_\mathrm{e}=125$. The predicted spectral index of $\alpha=0.17$ is also consistent with observed values (Falcke et al. 1988) and with the electron energies we found one could in principle explain the (sub)mm-bump in the spectrum as emission arising from the inner nozzle region of the jet (see Falcke 1996a). On the other hand there is currently no evidence for any emission of Sgr A* at other wavelengths than the radio, suggesting that any accretion "disk" emission is well below 10^{38} erg/sec and therefore—unlike in the other sources—is well below the required jet-power.

4. Discussion and Conclusion

4.1. Model fitting

The results of the model fitting in the previous section has a number of interesting consequences and caveats. The fact that all radio cores can be fitted with one simple model is already important, since the sources discussed here are so well constrained that by far not all combinations of size and flux could be fitted by the model. What is, however, more striking is the fact that the parameters required to explain sizes and fluxes are very similar. Firstly, in all sources the typical Lorentz factor of the electrons is of the order of a few hundred. Given the extreme simplicity of the model and the extensive use of equipartition assumptions (departing from which would be reflected in a change of γ_e as well) this similarity points to a relatively similar internal structure of the radio cores. Secondly, all sources have jet-powers very close to or larger than the luminosity of their thermal radiation, i.e. the suspected accretion disk luminosity. Since the model was constructed such that the radiative efficiency is maximal, applying more realistic models—for example by using different equipartition factors, velocity fields, or electron distributions—will therefore in almost all cases only lead to an increased demand for jet power in these sources.

The model fits perhaps most convincingly the jet in GRS 1915+105, where it not only reproduces core size and flux very well, but apparently also predicts radio time delay and jet velocity reasonably well. The latter indicates that perhaps the pressure gradient in the jet of GRS 1915+105 is mainly responsible for reaching its asymptotical velocity—unless higher velocities are found in future observations.

4.2. Limitations

We note that for determining Q_jet from the jet model, the flux and to some degree the inclination angle (especially for small i) are most important, while γ_e is mainly determined by the size of the core. Consequently, the latter seems to be the most uncertain part since it is often ambiguous how to define the core and its characteristic size, especially when the resolution is of the order of the core size. Moreover, we have introduced γ_e mainly to easily reflect the possibility of a low-energy cut-off or break in the spectrum. This has the positive effect that cores can be larger than their size purely given by the $\tau=1$ surface (which is particularly useful in GRS 1915+105 and NGC 4258), however, it also means that the core size may depend sensitively on the evolution of the electron distribution which we have ignored almost completely. Hence, the predictive power of this model for radio core sizes is very limited and only good to an order of magnitude, so that we will not base our interpretation heavily on the sizes. It should also be noted that the jet model used here has been trimmed towards LLAGN to achieve the greatest possible degree of simplification with the assumption that their velocity field can be described by Eq. 1. We know that this does not apply to quasars where the bulk Lorentz factor of the jets seems to be larger and the fully parametrized equations (e.g. as in Falcke & Biermann 1995) have to be used.

However, taking all this into consideration we can give yet a more simplified formula where we have fixed γ_e at an intermediate value of 300 and which can be used to very roughly estimate the jet power of a LLAGN from its flux and presumed inclination angle alone:

$$Q_\mathrm{jet}=10^{39}\,\mathrm{erg/sec}\,\frac{0.024^{\frac{\xi_0}{\xi_1}}\,1.56^{\frac{\xi_4}{\xi_1}}\left(\frac{D}{10\mathrm{kpc}}\right)^{\frac{1.6}{\xi_1}}\left(\frac{S_\nu}{\mathrm{mJy}}\right)^{\frac{0.79}{\xi_1}}}{\left(\frac{M_\bullet}{33M_\odot}\right)^{\frac{0.15\,\xi_2}{\xi_1}}\left(\frac{\nu}{8.5\mathrm{GHz}}\right)^{\frac{0.15\,\xi_2}{\xi_1}}\xi_3^{\frac{0.79}{\xi_1}}} \quad (20)$$

Source	D	i	$\nu_{\rm obs}$ [GHz]	S_ν [mJy]	size [mas]	$M_\bullet$ [$M_\odot$]	$L_{\rm disk}$ [erg/sec]	$Q_{\rm jet}$ [erg/sec]	lg $\gamma_{\rm e}$	α
GRS 1915+105*	12 kpc	70°	15	40	2	(33)	10^{39}	$10^{39.1}$	2.6	0.21
NGC 4258*	7.3 Mpc	82°	22	3	0.35	$3.5 \cdot 10^7$	(10^{42})	$10^{41.7}$	2.8	0.22
M81*	3.25 Mpc	35°	8.5	100	0.5	(10^6)	$10^{41.5}$	$10^{41.8}$	2.4	0.14
Sgr A*	8.5 kpc	(45°)	43	1100	~0.5	$2.5 \cdot 10^6$	$< 10^{38}$	$10^{38.7}$	2.1	0.17

Table 1. Parameters for compact radio core in various sources. Columns 2-7 are observationally determined input parameters: distance D, inclination angle i of disk axis and jet to the line of sight, observing frequency $\nu_{\rm obs}$, flux density of radio core S_ν, size of radio core, and black hole mass $M_\bullet$. The inferred disk luminosity $L_{\rm disk}$ is not an input parameter here and given in column 8 for comparison only. Uncertain values are given in brackets, but since the black hole masses do not enter strongly the uncertainties in the black hole mass for M81 and GRS 1915 are actually irrelevant. Columns 9-11 are output parameters of the radio core model: jet power $Q_{\rm jet}$, characteristic electron Lorentz factor $\gamma_{\rm e}$, and average spectral index α ($S_\nu \propto \nu^\alpha$) in the radio.

4.3. Jet/disk-symbiosis

The main result of this work, however, is that in three very different sources, with very different sizes and fluxes, we can explain the central core with a single model by just scaling the jet power with the accretion rate. This works because the three selected sources, GRS 1915+105, NGC 4258, and M81*, all have some very important ingredients in common. All three have clear evidence for a massive black hole, signs of (large or small scale) accretion disks, jet structures in their radio cores, and a good determination of the inclination angle (important for the fitting of individual sources). In GRS 1915+105 there is even direct evidence for a coupling between jet and disk from the light curves. The high jet power we derive for the radio core in a relatively quiescent phase is quite consistent with but lower than the power derived for the major outbursts (e.g. Mirabel et al. 1998).

In hindsight this high power in the radio cores justifies the assumptions we have made in earlier papers that jet and disk can be considered symbiotic systems and that—at least in a few systems—the assumption of $Q_{\rm jet}/L_{\rm disk} \sim 1$ (or even larger) seems appropriate. This also strengthens the picture that the jets are produced in the inner region of an accretion disk, where a major fraction of the dissipated energy is channeled into the jet (Falcke & Biermann 1995; Donea & Biermann 1996). As a consequence, modelling of accretion disks and X-ray light curves in jet systems like GRS 1915+105 clearly requires taking the jet into account.

4.4. Accretion disks and ADAFs

Another consequence from those radio cores is their amazing scale invariance. It seems that we can use the very same model for a stellar mass black hole which is accreting near its Eddington limit (GRS 1915+105) as well as for a super-massive black hole which is presumably accreting at an extreme sub-Eddington rate (M81, NGC 4258). Moreover a very similar model was successfully applied to a quasar sample earlier (Falcke et al. 1995), i.e. supermassive black holes near the Eddington limit. That would suggest that certain properties of an accretion disk/flow, namely jet production, is very insensitive towards changes in accretion rate or black hole mass, and that the 'common engine' mechanism of black hole accretion and jet formation, suggested by Rawlings & Saunders (1991), may include a much larger range of AGN than only quasars and radio galaxies.

If this is so, it has to be asked whether indeed every accretion flow necessarily has to make a transition from a thin α-disk to an ADAF when turning sub-Eddington. In order to maintain this proposition one then needs to explain how the accretion disk structure can change so drastically without affecting its innermost region, where jets presumably are being produced. If one asks what the arguments for ADAFs in low-power AGN really are, the evidence remains thin. For NGC 4258 it is quite obvious now that the radio core cannot serve to support an ADAF emission model. Quite contrary the derived jet power is consistent with a low accretion rate, which in turn is consistent with the low luminosity of the nucleus and, of course, a thin disk is directly seen at least at larger radii. With the radio emission gone the ADAF spectral energy distribution, extending over many orders of magnitude, merely serves to explain a single X-ray data point. Hence, it is currently not obvious that an ADAF is really needed to explain this source at all.

The same seems to be true for M81, which is equally sub-Eddington as NGC 4258. Here the situation is even worse, since Ishisaki et al (1996) also claim the detection of a broad iron Fe-K line suggesting that probably the inner disk cannot be as hot as required in an ADAF model. As similar broad line has been tentatively claimed also for NGC 4258 by Cannizzo et al. (1997). In any case the two galaxies serve as a general warning to view the existence of a compact radio core in low-luminosity AGN as prima facie evidence for an ADAF—a jet origin may be a more natural explanation here and in other cases. We also want to point out that the argument by Narayan et al. (1995) a pure ADAF interpretation of radio cores were superior because the latter requires an 'additional' emission component is not quite true if one considers disks and jets to be symbiotic, i.e. to be essentially one system.

*4.5. Sgr A**

So far we have concentrated the discussion mainly on the three sources which fitted the model well and have not mentioned Sgr A*. The jet-power we derive for the latter source now is virtually unchanged with respect to the power used to introduce the Sgr A* jet model in Falcke et al. (1993) and it still explains the radio properties of Sgr A* very well. However, as pointed out in this earlier paper already, the required jet power also provides a *lower limit* to the accretion rate onto the black hole of $10^{-7}M_{\odot}$/yr (using the current numbers and ignoring unlikely small inclination angles). Yet, even such a low accretion rate seems to be excluded on the basis of very stringent upper limits for the NIR flux of Sgr A* placed by Menten et al. (1996, see also Falcke & Melia 1997 for a discussion of this point). If one ignores the possibility of intrinsic obscuration in the Galactic Center this indeed seems to indicate a very low radiative efficiency of the accretion flow onto the black hole and, ironically, the jet model may provide in this case supporting argument for advection. As an alternative model one could envisage a scenario where the missing energy, instead of being radiated away, is put almost completely into a (magnetically) driven wind throughout the disk—this, however, would need to be worked out in more detail. As a side note we also want to mention that the low $\gamma_{\rm e}$ we derive for Sgr A* requires a relativistic electron fraction of ~ 3. A value for $x_{\rm e}$ significantly larger than unity is only possible if additional pairs were produced and thus could support the suggestions by Falcke (1996b) and Mahadevan (1998) that pair production through proton-proton collisions is at work here. However, as pointed out before, the determination of $\gamma_{\rm e}$ and especially its interpretation within our simple model is fairly unreliable and hence should be taken very cautiously.

4.6. Summary

To summarize this section, we believe that the jet model does seem to provide an excellent description of nuclear radio cores also in LLAGN and that considering jets and disks as symbiotic systems can explain the vast range of radio core luminosities and sizes we find in the nuclei of galaxies and in stellar mass black holes. Comparison of jet powers and nuclear luminosities of some radio cores seem to indicate that they are of similar order, thus supporting an under-fed black hole scenario with low accretion rates. Consequently, even though they are not excluded, ADAFs need not be as ubiquitous in low-luminosity AGN as has been claimed while the jet interpretation for compact radio nuclei seems to be a natural interpretation also for low-luminosity AGN. It therefore does not appear as if the presence of a compact radio core and a low optical luminosity alone serve as a good indicator for an ADAF. On the other hand—as the example of Sgr A* shows—a jet interpretation of low-luminosity radio cores could in some cases support the presence of an advection dominated accretion flow or some other kind of radiatively deficient accretion disk. Therefore a combination of ADAF and jet models should also be considered for the fitting of nuclear spectral energy distributions.

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