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Galactic jet sources and the AGN connection

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Abstract. In order to further test our hypothesis that jets and disk around compact accreting objects are symbiotic features we investigate the newly discovered superluminal galactic radio jets GRS 1915+105 and GRO J1655-40 and other galactic radio jets like 1E1740-2942, GRS 1758-258 and SS 433 within the framework of our coupled jet/disk model developed initially for active galactic nuclei (AGN) and the galactic center source Sgr A*. By comparing the "disk" and radio core luminosity of those galactic jet sources with our model prediction we can show that they can easily be understood as AGN-like jets where the accretion power onto a central compact object is scaled down by several orders of magnitude. The total power of the jets must be comparable to the disk luminosity - at least for the superluminal sources.

To broaden our view we also shortly discuss the situation in other galactic flat spectrum radio sources associated with compact objects – the X-ray binaries Cyg X-1, Cyg X-2, Cyg X-3, Sco X-1, Cir X-1 – where a jet origin has been proposed earlier on theoretical grounds. In a disk/radio luminosity diagram their radio cores also fall within our model prediction for scaled down radio loud and radio weak AGN-jets. Taking all sources together and comparing their $L_{\rm disk}$/radio ratio we find an indication for a similar radio loud/radio weak dichotomy as found earlier for quasar radio cores, however, a larger number of galactic jet sources is needed to confirm this trend.

Key words: stars: GRS 1915+105 – stars: GRO J1655-40 – galaxies: active – galaxies: jets – galaxies: nuclei – accretion

1. Introduction

Bipolar outflows with velocities close to the speed of light are found in the nuclei of many active galaxies (AGN) and are believed to be powered by a central engine consisting of a super massive black hole and an accretion disk. In previous papers we investigated the energy balance of these systems (Falcke, Mannheim, Biermann 1993, (FMB93); Falcke & Biermann 1995 (Paper I); Falcke, Malkan, Biermann 1995, (Paper II); Falcke, Gopal-Krishna, Biermann 1995; see also Falcke (1996) for a summary) and started with the basic hypothesis that jets and disks around compact accreting objects are symbiotic features. We found that a closely coupled jet/disk system can explain such a variety of phenomena as the UV/radio correlation of radio loud and radio weak quasars and the unusual radio properties of the Galactic Center source Sgr A*. Of course it is not possible to prove the symbiotic nature of jets and disks here (i.e. that they are always both present) but our aim is to check how far we can get with such an assumption and test it for as many different object classes as possible.

Recently, it was shown that the relativistic jet phenomenon can be found inside the Galaxy as well, again in systems which are suspected to harbor ultra-compact central objects – most likely stellar mass black holes (or neutron stars) – surrounded by accretion disks (e.g. GRS 1915+105 & GRO J1655-40, see Mirabel & Rodriguez 1995 for a review). This was not unexpected within the framework of our approach and hence, we now want to apply our analysis of jet/disk systems to these objects as well and test if the previous found $L_{\rm disk}$/radio correlation for AGN extends down to stellar mass black holes.

The similarity between these galactic jet sources and AGN is often stressed, but does this also have a physical foundation other than a pure morphological similarity? Are both engines powered by accretion onto a compact object producing radio jets? If AGN and galactic jet sources were indeed to be of similar origin, they still should be understandable within the same simple physical description despite the scales being vastly different. Such a very simple description was outlined in Paper I and successfully tested in Paper II for AGN and in FMB93 for Sgr A* – already very different systems. There we were able to account for the observed properties by assuming that only a few important parameters – like the mass accretion

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rate and the black hole mass – change, while most others, like the ratio of jet power to disk luminosity or the fraction of relativistic electrons, remain largely scale invariant. We also found that indeed mass and energy conservation are serious constraints for coupled jet-disk systems and therefore imply interesting conclusions, e.g. about the energization of electrons. If we were to find similar results for the galactic jet sources then indeed one had more reason to believe in a physical relationship between galactic jet sources and AGN. Hence, in this paper we are not interested in a detailed modelling of individual sources but simply apply our AGN model to low power jet sources without further fitting of parameters.

The plan of the paper is as follows: we first will introduce the sources we are using (Sec. 2), then discuss the expected values of $L_{\rm disk}$ (Sec. 3.1) and $L_{\rm jet}$ (Sec. 3.2) for galactic jet sources using our model description (see Sec. 3.3 for a short discussion of the parameters) and finally construct a *radio*/$L_{\rm disk}$ diagram for galactic and extragalactic jet sources followed by a discussion of the results.

2. The sources

The sample of galactic jet sources we investigate is not at all properly selected as we took just the prominent sources which have received substantial attention in recent years. The sources are listed in the following.

GRS1915+105 – the first galactic jet source found to have superluminal motion (Mirabel & Rodriguez 1994, hereafter MR94). This source was studied with the VLA because of its frequent X- and Gamma-ray bursts. After one of these outbursts Mirabel & Rodriguez detected a radio blob obviously being ejected from the central source. The derived expansion speed was 1.2 c. This phenomenon is well known from extragalactic flat spectrum radio sources (mostly blazars and core dominated quasars) and usually interpreted as a relativistic effect caused by a radio jet with bulk velocity close to the speed of light pointing towards the observer. Thanks to a sufficient data base collected for the March 19, 1994 outburst MR94 were able to determine the physical properties of the expelled radio blobs, i.e. a true velocity of $v_{\rm jet}=0.92c$ and inclination of the jet axis $i=70^\circ$ with respect to the line of sight at a distance of $D=12.5$ kpc.

GROJ1655-40 – an X-ray nova detected with BATSE in Scorpio which was followed by the expulsion of radio ejecta apparently at superluminal speeds (Tingay et al. 1995), making this source the second confirmed superluminal jet in the Galaxy. More detailed VLBI studies have confirmed that the interpretation of relativistically moving jets gives an amazingly good description of the source properties (Hjellming & Rupen 1995) with an intrinsic speed of $\sim$ 0.92c. The source seems to be highly inclined with an angle of $i=84.5^\circ$.

1E1740-2942 – The first galactic jet source found to resemble an extragalactic jet was the 'great annihilator' 1E1740.7-2942 – a putative black hole showing a miniature FRII type jet structure located inside a giant molecular cloud (Mirabel et al. 1992). There is a weak central core and two lobes 1 pc away. This is one of the few sources where a broad electron/positron (e^+e^-) annihilation line was claimed to have been observed by the experiment SIGMA on GRANAT (Bouchet et al. 1991). The canonical model is a compact object, accreting from the molecular cloud in an accretion disk which produces a radio jet flowing out along the rotation axis of the system.

GRS 1758-258 – Following a suggestion of the referee we consider this source as well, as it resembles 1E1740-2942 in many respects. It is a persistent bright hard x-ray source in the Galactic Center with a spectrum typical for a black hole candidate (Sunyaev et al. 1991). VLA observations by Rodriguez et al. (1992) showed the presence of a highly elongated radio counterpart which one might well interpret as a jet.

SS433 – is a famous binary system with highly red- and blue-shifted emission lines due to the ejection of dense gas linked to a mildly relativistic precessing radio jet moving with a speed of $v_{\rm jet}=0.26c$ (see Margon 1984). It is often seen as the archetype for any galactic jet source although it is quite unique in various respects (i.e. strong precession of jet axis, weak x-ray flux). It may well harbor a thick supercritical accretion disk rather than the usually inferred thin disk. One of the stars is supposed to be either a neutron star or a black hole.

X-ray binaries – There is a whole class of objects, the x-ray binaries, which are assumed to consist of compact objects (neutron stars or black holes) and show (variable, flat spectrum) radio emission. Hjellming and Johnston (1988) proposed that sources like Cyg X-1, Cyg X-2, Cyg X-3, and Sco X-1 may also have conical jets somewhat similar to SS433. Therefore, we will also include these sources to compare their radio/x-ray properties to those of the confirmed jet sources. Another source pointed out to us by the referee is Circinus X-1 – probably a runaway-binary – which explicitly shows a bend jet structure.

Quasars, Sgr A, M31** – We will compare the newly added, low-mass sources with the previously discussed PG-quasar sample (Paper II) and the nearby supermassive black hole candidates in the Galaxy (Falcke et al. 1993a&b, Falcke & Biermann 1994, Falcke 1994 & 1995) and M31 (M31*) (see Falcke & Heinrich 1994). The latter do not have confirmed radio jets but compact radio cores which may be explained as such. The quasar sample includes typical radio loud FRII-type radio quasars and radio weak quasars. In Paper II we have argued that their radio emission can as well be attributed to a central radio jet.

3. $L_{\rm disk}$/radio correlation

3.1. Disk luminosity

The theory of viscous accretion disks is canonically described by the Shakura & Sunyaev (1973) α-disk model and its relativistic extension by Novikov & Thorne (1974). The characteristic effective temperature of accretion disks $T_{\rm eff}$ is fairly independent of the details of the viscosity mechanism and merely depends on the mass of the black hole $M_\bullet$ and the accretion rate $\dot{M}_{\rm disk}$, the total disk luminosity $L_{\rm disk}$ depends on $\dot{M}_{\rm disk}$ only and we have (see e.g. Falcke et al. 1993a)

$$\nu_{\rm max} = 0.7\cdot 10^{18}\,\frac{\dot{m}_{-8}^{1/4}}{m_\bullet^{1/2}}\frac{\left(r^{-3}\mathcal{Q}\mathcal{B}^{-1}\mathcal{C}^{-1/2}\right)^{1/4}}{0.1}{\rm Hz}, \tag{1}$$

$$T_{\rm eff} = 1.2\cdot 10^{7}{\rm K}\left(\frac{\nu_{\rm max}}{10^{18}{\rm Hz}}\right) \tag{2}$$

and

$$L_{\rm disk} = 3\cdot 10^{37}\dot{m}_{-8}\left(\frac{\eta}{5\%}\right)\,{\rm erg/sec}. \tag{3}$$

Here $m = M_\bullet/M_\odot$ and $\dot{m}_{-8} = \dot{M}_{\rm disk}/10^{-8}(M_\odot/{\rm yr})$ are the dimensionless mass and accretion rate of the black hole. $r = R/R_{\rm g}$ is the dimensionless radius in units of the gravitational radius $R_g = GM/c^2 = 1.48\cdot 10^5 M/M_\odot$cm which is half the Schwarzschild radius. The relativistic correction factors $\mathcal{B}, \mathcal{C}$ and $\mathcal{Q}$ are functions of r and are given explicitly in Page & Thorne (1974). The efficiency η for black holes varies between $5\% - 30\%$ depending on their angular momentum.

With $T_{\rm eff}$ and $L_{\rm disk}$ one can simply construct a Hertzsprung-Russell diagram for black holes and their accretion disks (Falcke et al. 1993a, Falcke & Biermann 1994), where each combination of mass and accretion rate has its well defined place in the $T_{\rm eff}/L_{\rm disk}$ plane. Quasars with supermassive black holes and high accretion rates for example can be found around $L\sim 10^{44}-10^{48}$ erg/sec and $T_{\rm eff}\sim 10^{4-5}$ K while solar mass black holes have $L_{\rm disk}\sim 10^{36-38}$ erg/sec and $T_{\rm eff}\sim 10^7$ K. In order to discuss a possible $L_{\rm disk}$/radio correlation over such a broad range of parameters it is not viable to simply compare one small frequency range with another: this may work for a homogenous class of objects like quasars, where an UV/radio correlation can be found, but going from quasars to stellar mass black holes one obviously has to shift from the UV to the x-ray regime (Eq. 1), where the bulk of the accretion disk luminosity is radiated.

3.2. Jet-disk coupling

In a series of papers (FMB93; Paper I; Paper II; Falcke 1994&1996) we have investigated the correlation between accretion disk luminosity ($L_{\rm disk}$) and radio luminosity in quasars as well as in the Galactic Center source Sgr A*. We found a tight correlation between $L_{\rm disk}$ and radio emission in radio loud and radio weak quasars (Paper II) and explained this as the consequence of a closely coupled jet/disk system in the nuclei of these galaxies. By adding mass and energy conservation in a jet/disk system to the classical Blandford & Königl (1977) emission model for radio cores (Paper I) we showed that any jet/disk coupling imposes serious constraints on the possible source parameters (Paper II). The most important finding was that the total jet power $Q_{\rm jet}$ is a substantial fraction of the disk luminosity $L_{\rm disk}$ as was already suggested in a seminal paper by Rawlings & Saunders (1991). This suggests that jet formation is directly coupled to the dissipation mechanism in the disk and occurs very close to the black hole (Paper I).

If we express the parameters of the jet radio emission in a scale invariant form and assume that the jet emission is caused by the overlap of synchrotron self-absorbed components in a conically shaped jet, fed by the accretion disk, and transporting a tangled magnetic field gradually declining as $B\propto r^{-1}$ one obtains a flat total radio spectrum (Paper I, Eq. 57) from one jet cone

$$L^*_{\nu_{\rm s,obs}} = 2.5\cdot 10^{21}\,\frac{\rm erg}{\rm s\,Hz}\,\left(q_{\rm j/l}L_{38}\right)^{17/12} \cdot\frac{\mathcal{D}^{13/6}\sin i_{\rm obs}^{1/6}\left(\gamma_{\rm e}x_{\rm e}\right)^{5/6}}{\gamma_{\rm j}^{11/6}\beta_{\rm j}^{5/12}u_3^{7/12}} \tag{4}$$

Here, it is assumed that magnetic field, turbulent motion and relativistic particles ($u = 3u_3$) are in equipartition and form a relativistic plasma with maximal sound speed. The latter requires also equipartition between kinetic and internal energy. This *maximal* jet (see Paper I) is the radiatively most efficient type of jet one can get for a given total jet power $Q_{\rm jet}$, and as we showed in Paper II less efficient jet models fail to explain the radio emission of radio loud quasars. We now only assume that the total jet power scales with the disk luminosity ($Q_{\rm jet}\lesssim L_{\rm disk}$) and thus obtain Eq. 4.

The parameters introduced are the ratio of the total power of one jet cone to disk luminosity $q_{\rm j/l} = 0.5Q_{\rm jet}/L_{\rm disk}$, the disk luminosity $L_{38} = L_{\rm disk}/10^{38}$ erg/sec, the ratio between the number density of relativistic electrons to the number density of protons $x_{\rm e}$ (without pair creation $x_{\rm e}\le 1$), $\gamma_{\rm e}$ is the minimum Lorentz factor of the electrons, i the angle between jet-axis and the line of sight, $\mathcal{D}$ is the Doppler factor of the jet, $\beta_{\rm j}c$ and $\gamma_{\rm j}$ are bulk velocity and Lorentz factor of the jet.

The reason for the non-linear dependence of F_ν on $L_{\rm disk}$ is simply due to the fact that the synchrotron emissivity in the equipartition case depends non-linearly on the magnetic field energy density; in addition there is a minor effect induced by different spectral shapes for different electron energy distributions which we assume to be a powerlaw with exponent 2.

For an edge-on system of two jet cones in the Galaxy (D=8.5 kpc) we get (ignoring Doppler boosting and inclination effects, setting $q_{\rm j/l}=0.15$ as in Paper II)

$$F_\nu \;=\; 4\,{\rm mJy}\cdot L_{38}^{1.4}\left(\gamma_{\rm e}x_{\rm e}\right)^{.83}\beta_{\rm j}^{0.42}\gamma_{\rm j}^{1.8}, \tag{5}$$

the physical scale corresponding to this flux at cm wavelengths is

$$z_{\rm jet}(\nu)\;\simeq\;3\cdot10^{13}\,{\rm cm}\,\left(\frac{\nu}{1\,{\rm GHz}}\right)\left(\gamma_{\rm e}x_{\rm e}\beta_{\rm j}/\gamma_{\rm j}L_{38}^2\right)^{1/3} \tag{6}$$

which is of the right order for radio weak sources. One has to note that $z_{\rm jet}(\nu)$ corresponds to a distance where the jet becomes optically thick at the specified frequency. This has to be taken into account when one discusses radio outbursts and ejection of blobs. Although an evolving single blob is not really properly described by our emission model, the best comparison between the radio flux at one frequency and the model will be possible at that point in time where the blob spectrum turns over and becomes optically thick at this frequency. The blob evolution seen by VLBI and VLA usually depicts later stages of the evolution.

When comparing those highly time dependent events with our stationary model one also has to consider that there may be different time scales involved for the jet and the disk (battery effect), hence, the relation Eq. (4) may be violated in strong outbursts. In the comparison of outburst stages with the would-be-stationary calculation large time scale differences should show up as strong deviations from the model.

3.3. Parameters

We now shortly discuss the various parameters entering the model:

3.3.1. Total jet power

For quasars we found (Paper II) that the ratio between jet power and disk luminosity was around $2q_{\rm j/l}=0.3$. Substantially lower jet powers were not able to explain radio loud jet cores – even with the most efficient models. As we assume that this parameter reflects an universal jet/disk coupling mechanism, we will keep that value fixed in the further discussion.

3.3.2. Jet velocity

In Paper II we discussed the possibility of a scaling of the proper jet velocity with disk luminosity but did not find a strong effect. However, we found that a weak power-law dependence with exponent $\xi=0.15$ is quite consistent with the data (Paper II, Eq. 11). In contrast to quasars we know the jet velocities in the galactic superluminal sources quite well which are in the range (0.7-0.9)c and we can fix the velocities at the measured values. For a smooth transition from AGN to galactic jets we therefore slightly modify the scaling law to include a lower limit for the jet speed yielding

$$\gamma_{\rm j}\beta_{\rm j}=\gamma_{46}\beta_{46}\left(\left(\frac{\gamma_0\beta_0}{\gamma_{46}\beta_{46}}\right)^{1/\xi}+\frac{L_{\rm disk}}{10^{46}{\rm erg/sec}}\right)^{0.15}, \tag{7}$$

where $\gamma_0\beta_0\sim2$ is the proper jet speed of the low-power jet sources and $\gamma_{46}\beta_{46}\sim6$ the proper jet speed of quasars with $L_{\rm disk}=10^{46}$ erg/sec.

The previously used pure powerlaw with $\gamma_0\beta_0=0$ would have predicted $\beta_{\rm j}\sim0.4$ for systems with $L_{\rm disk}\sim10^{38}$ which is still in the right ball-park but slightly too low to produce the relativistic effects in GRS 1915+105 and GRO J1655-40. At present we do not attribute any physical significance to this scaling law, use it mainly for practical reasons, and will not adjust the correct value for each individual source as the changes due to a different jet speed in the regime $\beta\lesssim0.8$ are smaller than the overall uncertainties of the model.

3.3.3. Electron content: radio loud – radio quiet

Choosing a relativistic electron content of the jet with $\gamma_{\rm e}x_{\rm e}\sim1$ would correspond to a situation where the jet is already very energetic, however, the radiative efficiency is limited by the number of available electrons in the flow which have all been accelerated into a power law distribution. Neither magnetic field nor the number of electrons can be further increased without violating energy and mass-conservation in the jet/disk system to produce more radio emission even though the electrons are not yet in equipartition. One can only alter the distribution of the electrons by raising their number through additional pair-creation ($x_{\rm e}\lesssim100$, e.g. mixed or pure electron/positron jet) or injecting the electrons already at a high energy where they become energetically dominant ($\gamma_{\rm e}\lesssim100$, see Paper I). The latter is what must happen somehow in radio loud quasars (Paper II) and applied to Eq. (5) means that one may expect fluxes of ~100 mJy up to a few Jy for the Eddington limit of stellar mass black holes.

In Paper II we tentatively identified a maximal jet with $\gamma_{\rm e}=1$ & $x_{\rm e}=1$ (all electrons accelerated from thermal pool but only protons are in equipartition with the magnetic field) as the radio quiet state and $\gamma_{\rm e}=100$ (electrons and protons in equipartition with magnetic field, electrons injected at high energies) as the radio loud state – both are natural states within any jet model. The radio loud model is the radiatively most efficient situation and for a given $Q_{\rm jet}/L_{\rm disk}$ also is the upper limit to the possible radio emission - one would strongly suspect that $Q_{\rm jet}/L_{\rm disk}\lesssim1$ in a normal system.

One way to obtain the injection of synchrotron radiating particles at $\gamma_e \gtrsim 100$ and make jets radio loud can be the pion-decay in hadronic cascades which in turn could be initiated by *pp* collisions of relativistic protons in the jet with thermal protons in the shear layer between jet and surrounding medium (see Paper I&II, Falcke 1995).

4. A universal $L_{\rm disk}$/radio correlation?

4.1. Application of the model

We now want to apply our scaling laws (Eq. 4) to the galactic radio jets and compare them with other known jet sources. We will take the same model as in Paper II with just the parameters used to describe the radio/UV correlation in quasars ("maximal" radio loud and radio weak jets with $q_{\rm j/l} = 0.15$ and $\gamma_{\rm jet}(L_{\rm disk} = 10^{46}{\rm erg/sec}) = 6$).

The width of the model prediction (Fig. 1) is determined by the spread of possible inclination angles in conjunction with relativistic boosting. The shaded band limits the range between 15 and 90 degree, while the thin line represents the 0 degree inclination case. As this spread is smaller for lower jet velocities ($\beta < 0.8$) those models are simply contained within the range of the presented model.

One should remember that for quasars the lower part of each band is probably not populated because of obscuration by a torus. The bend in the bands reflects the turnover from highly to mildly relativistic jets. Figure 1 was already presented in Falcke (1994) – before the discovery of the superluminal sources and the determination of their velocities – for slightly lower jet velocities, but despite the bands being somewhat narrower it already represented the same basic results.

4.2. Observational data for individual sources

The next step is to compare $L_{\rm disk}$ and radio core fluxes for the different object types with the basic jet model. We first reproduced Fig. 3a from Paper II, where we compared UV-bump and VLA radio cores of a quasar sample with the model of Paper I, and extended the plot range to very low disk luminosities. Moreover, we added Sgr A* and M31* as already discussed in Falcke et al. (1993a), FMB93 and Falcke & Heinrich (1994).

We then estimated the disk luminosities for the galactic jet sources GRS 1915+105, GRO J1655-40, and 1E1740-2942 from their X-ray observations where we differentiated between high and low states if required. The accretion disk luminosity of SS433 was already extensively discussed in the literature. Those numbers are given in Table 1 and more detailed comments and references for the individual sources are given in the appendix. In addition we collected the 5 GHz flat spectrum core fluxes of the jets corresponding to the sources in their different states as listed in Table 1 and discussed in the Appendix. For the outburst sources we either took the peak x-ray luminosities and the flux when the spectrum appeared flat at 5 GHz in an outburst. We then did the same for the X-ray binaries. When several datapoints of a variable source were available we choose the logarithmic mean value of the radio flux (in low and high states respectively) as we did in Paper II already.

4.3. Results

The combined plot of these sources together with the model is shown in Figure 1. One can see that in fact most sources directly fall in the predicted range and none really is far off, only Sco X-1 seems to have a somewhat low radio flux compared to its x-ray luminosity. The sources also seem to be divided into two branches separated by roughly 2-3 orders of magnitude.

Considering the uncertainties we at least can positively state that each of those sources could in principle be explained by a jet model within the constraints of mass and energy conservation in a coupled jet/disk system as outlined in Paper I.

To highlight the separation of the two branches, we calculated the ratio between the radio luminosity at 5 GHz and the disk luminosity for each source (Table 1), yielding something like the R parameter used in the description of radio loudness of quasars

$$R = \frac{\nu L_\nu(5{\rm GHz})}{{\rm L_{disk}}}. \tag{8}$$

We plotted this R parameter versus the disk luminosity of the sources (Fig. 2); there indeed appears to be a separation into a radio loud branch with $\log R > -6$ and a radio weak branch with $\log R < -8$. For comparison we note that on average $<\log R>= -3.8$ and $<\log R>= -6.3$ for radio loud and radio weak quasars, and $<\log R>= -5.7$ and $<\log R>= -8.4$ for radio loud and radio weak low power sources respectively.

In Fig. 2 we also labeled the individual sources which makes it easier to also locate them in Figure 1. Most x-ray binaries (Sco X-1, Cyg X-1, Cyg X-2) in high and low states fall in the radio weak regime occupied by 1E1740-2942, GRS 1758-258 and SS433. On the other hand Cyg X-3 falls on the radio loud branch occupied by the starved supermassive black holes Sgr A* and M31* and the superluminal jets GRO J1655-40 and GRS 1915+105. The latter are located at the uppermost end of the model which is inconsistent with them being relativistically de-boosted, but having the warning in mind that for this source we compare a time dependent outburst with a stationary model we can allow a certain factor that leads to an enhancement of the radio emission. In the low states both jet sources are well within the model predictions where the low radio state of GRS 1915+105 even falls completely onto the radio weak branch while the case for GRO J1655-40 remains

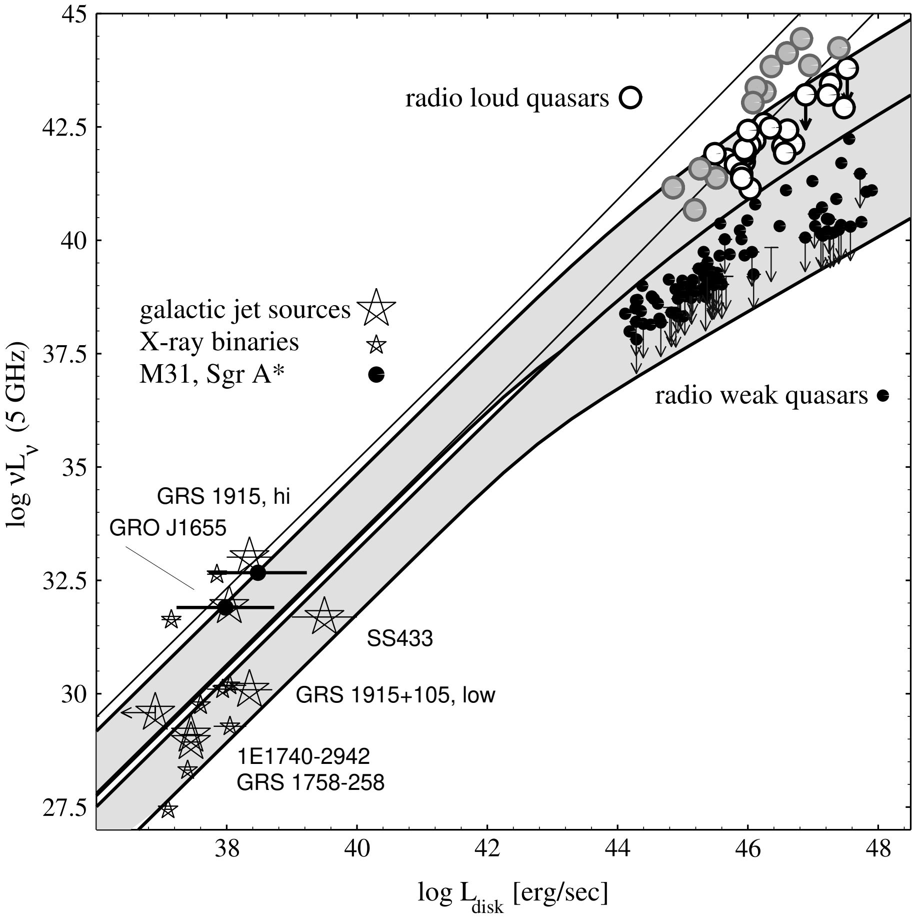

Fig. 1. Monochromatic luminosity of the compact radio core versus the disk luminosity for AGN (above 10^{43} erg/sec, see Paper II for details) and galactic jet sources (stars). The two dots among the galactic jet sources are Sgr A* and M 31*, the x-ray binaries are represented by smaller stars. The shaded band gives our jet model for inclination angles of 15° to 90°, the upper lines indicate emission seen within the boosting cone (0-15 degree).

less clear due to the non-detection in x-rays. Cyg X-3 remains radio loud even in the low state. If we would have included the radio outbursts of Cir X-1 with $F_\nu \gg 100$ mJy, then this source would appear also in the radio loud branch.

5. Discussion

In Paper I we derived a simple jet model by adding mass and energy conservation in a jet/disk system to a simple sychrotron emission model of jets first developed by Blandford & Königl (1979). This model is derived from first principles and is fairly universal as it simply describes the dependence of a synchrotron emitting jet source on simple plasma parameter. By parametrization of this model in terms of the power available in an accretion disk thought to power the jet, we obtained a model which does not have an intrinsic scale other than the power of the accretion disk. Therefore we suggested that it should be applicable to all types of radio jets. And indeed it was possible to use the same kind of model for a low power jet source like Sgr A* and high power sources like quasars.

We have now extended this analysis and compared the overall radio properties of the cores of galactic jet sources and x-ray binaries with their disk luminosity. We again find a trend of increasing radio luminosity with increasing disk power. There also appears to be a separation in radio loud and radio weak sources. While the radio loud sources have an R-ratio between radio luminosity at 5 GHz and disk luminosity of $R \sim 10^{-5..-6}$, radio weak sources have $R \sim 10^{-8..-9}$. Given the large offset between radio loud and radio weak this dichotomy should prevail even if some of the measurements were in error, but considering the small number of sources and their ill defined selection criterion we can not exclude that this is caused by a selection effect. Nevertheless, this is reminiscent of the situation in quasars and may be an interesting trail to be followed in future research.

So far GRO J1655-40, Cyg X-3, Sgr A*, and M31* appear to be radio loud, while Sco X-1, Cyg X-1, Cyg X-2, 1E1740-2942, GRS 1758-258 and SS433 appear radio

Object	state	D [kpc]	$F_{5\rm GHz}$ mJy	$L_{\rm disk}$ [erg/sec]	log R
GRS 1915+105	low	12.5	1	$3 \cdot 10^{38}$	-8.3
	outburst		655	$3 \cdot 10^{38}$	-5.3
GRO J1655-40	low	4	4	$< 8 \cdot 10^{36}$	>-7.4
	outburst		900	10^{38}	-5.3
1E1740-2942	normal	8.5	0.3	$3 \cdot 10^{37}$	-8.4
GRS 1758-258	normal	8.5	0.2	$2 \cdot 10^{37}$	-8.5
SS 433	normal	4.85	350	$1 - 10 \cdot 10^{39}$	-7.8
Cyg X-1	normal	2.5	15	$4 \cdot 10^{37}$	-7.8
Cyg X-2	low	8	0.5	$1 \cdot 10^{38}$	-8.8
	high		4	$1 \cdot 10^{38}$	-7.9
Cyg X-3	low	8.5	100	$1 \cdot 10^{37}$	-5.5
	high		10^{3-4}	$1 \cdot 10^{38}$	-5.3
Sco X-1	low	.5	10	$1 \cdot 10^{37}$	-9.6
	high		1	$3 \cdot 10^{37}$	-9.1
Cir X-1	1989.3	6.5	5	$1 \cdot 10^{38}$	-7.8

Table 1. Parameters of the considered objects. Col.(1): object name, Col. (2): state of the object (high, low, outburst), Col. (3): distance assumed, Col. (4): approx. mean disk luminosity, Col. (5): mean radio flux at 5 GHz, Col. (6): log of ratio between radio luminosity at 5 GHz and disk luminosity

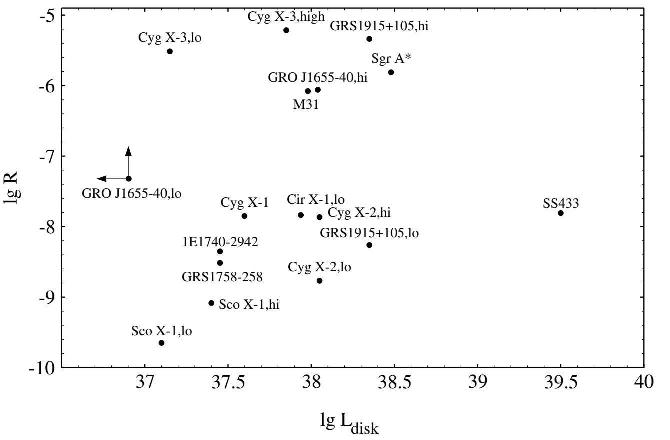

Fig. 2. The logarithm of the ratio R between radio luminosity at 5 GHz and disk luminosity for the galactic jet sources.

weak. GRS 1915+105 is the only source that varied by a factor 1000 while its x-ray luminosity was roughly constant and therefore moved from the radio loud branch in the high state to the radio weak branch in the low state. Only Cir X-1 might be a similar case if one considers its frequent radio bursts in the past. The reason for this behaviour is yet unclear but it may simply have to do with the highly non-stationary situation in these sources, e.g. the sudden release of stored energy or the sudden injection of relativsitic electrons.

Comparing the luminosities with our model prediction we found that, like quasars, galactic jet sources and our x-ray binaries can as well be explained within the same simple physical description of an outwards moving, synchrotron emitting plasma in a radio jet being fed by an accretion disk. Interestingly, the same intrinsic model parameters as used for extragalactic jets have to be used for galactic jet sources as well. These parameters are the ratio between jet power and disk luminosity which must be very high ($Q_{\rm jet}/L_{\rm disk} \sim 0.3$), the minimum Lorentz factor of the radiating electrons which has to be $\sim$ 100 at the time of injection for the radio loud sources (or alternatively 100 fold more particles by pair creation) and the state of the plasma which has to be near relativistic[1] and near its equipartition value (between magnetic field and relativistic particles). Only the jet velocities seem to be slightly smaller in low power jets than in quasars. Thus the radio loud galactic jet sources are already near the most efficient state as far as their radio emission is concerned which means that we have no freedom any more in choosing the plasma parameters.

The fact that some low-power radio loud jets are even slightly above our model prediction could be explained by differences in the variability time scales, however might also indicate that the ratio $Q_{\rm jet}/L_{\rm disk}$ could approach or even exceed unity in some cases.

The similarity in the physical conditions in galactic and extragalactic jets shows that they very likely have also a physical link beyond mere morphological similarity – *they seem to have similar engines differing only in size and power*. Thus it is no coincidence that both types of engines are usually interpreted as compact accreting objects. In our formulation the nature of this compact object is irrelevant and should be valid for black holes, neutron stars and perhaps even T Tauri stars[2]. However, if like in

[1] This would predict relativistic sound and expansion speeds in the blobs and could in principle be tested by VLBI observations

[2] Therefore it might be interesting to see if T Tauri stars would also fall in the radio vs. disk correlation. As the referee pointed out this might indeed be the case if (eg. T Tauri, d$\sim$ 160pc) $L \sim 7 \cdot 10^{34}$erg/sec ($17 L_\odot$, Beckwith et al. 1990) and

stellar wind theory, the terminal jet velocity scales somehow with the escape velocity at the sonic point – which usually is close to the base of the jet/wind – the terminal velocity could be a function primarily of the compact object. Rapidly rotating Kerr holes with high escape speeds would thus require relativistic jets while Neutron stars or Schwarzschild holes with lower escape speeds would require only mildly relativistic jets, stars would produce jets with only subrelativistic speeds. As the escape velocity close to a black hole at a fixed dimensionless radius $r = R/(GM_\bullet/c^2)$ is the same irrespective of the central mass $M_\bullet$ we could understand why the jet velocities in galactic and extragalactic jets are so similar despite 8-10 powers of ten difference in mass and mass accretion between both types. A similar argument concerning the difference in escape speed between black holes and neutron stars has been made by Mirabel and Rodriguez (1995, see their Tab. 1).

One may speculate – as we did in Paper I – that indeed jets are quite naturally associated with compact accreting objects but come in two flavors – radio weak and radio loud – depending on the energization of electrons. We proposed previously that those states could correspond to the situation where a) the thermal electrons ($\gamma_e \sim 1$) are smoothly (shock) accelerated into a powerlaw distribution b) electrons (or pairs) are shifted upwards in energy until the equipartition value is reached yielding a minimum Lorentz factor for the electrons of $\gamma_e \sim 100$. We note that one process that can inject pairs at such a high energy is the pion decay in hadronic cascades (see Falcke 1995, Falcke et al. 1995b, Biermann et al. 1995 for examples). Strong interaction of the relativistic jet with a dense environment at a scale of the order of $\lesssim 1$ AU could lead to *pp* collisions and thus to hadronic cascades. An observational signature of those cascades would be gamma-ray emission.

The similarity between the emission properties of galactic and extragalactic jets is highlighted in Fig. 1 where the same jet emission model connects high power and low power sources. Although we still do not have enough sources to firmly claim a $L_{\rm disk}$/radio correlation for galactic jet sources the results are already very promising. The hunch of a universal $L_{\rm disk}$/radio correlation for compact accreting objects extending from AGN down to stellar mass black holes as implied by Paper I&II and FMB93 is still consistent with all sources we tested. A future step to firmly establish such a correlation will be to investigate supermassive black hole candidates at intermediate powers between stellar mass black holes and AGN in nearby galactic nuclei and low-power Seyfert galaxies. In this sense one should understand Fig. 1 as a prediction for these sources.

It is interesting that also the sources where it is not yet rigorously shown that the radio emission is caused by jets like Sgr A*, M31*, Cyg X-3 and the other x-ray binaries mix with those sorces where there obviously are jets (SS433, 1E1740-2942, GRS 1758-258, GRO J1655-40, GRS 1915+105). This shows that the former can also easily be explained by a simple jet model but does of course not yet prove the existence of jets there. The observation that Cyg X-2 moves up and down within the radio weak band indicates that our treatment is indeed too simplified for a detailed discussion of the sources but on the large scale we still expect that further putative galactic jet sources will fall within the bands predicted by our model.

We finally conclude that the comparison of the flat spectrum core flux of compact accreting objetcs with their putative disk luminosity – the peak in the spectral energy distribution – may become a very powerful tool for the analysis and classification of such systems. What has to be done next is to extend the $L_{\rm disk}$/radio data set for compact accreting objects of stellar mass size in high and low states, and closely monitor the evolution of the superluminal jet sources to prove or disprove the notion of a universal $L_{\rm disk}$/radio correlation and the possible radio loud/radio weak dichotomy for galactic jet sources.

$\nu L_\nu(5GHz) \sim 10^{26}$ erg/sec ($\sim$ 1mJy, Schwartz et al. 1986) but it would probably require to modify the emission model.

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A. Appendix

The data used for the individual sources are discussed in the following:

GRS 1915+105 GRS 1915+105 was only recently discovered as an important object and has only a limited number of observations available. Using the VLA at 3.6 cm MR94 measure a 8 GHz flux of the slightly resolved source of 655 mJy at March 24, 1994 corresponding to 841 mJy at 5 Ghz for the spectral index 0.49. This was right after the ejection of the radio blobs. The same authors earlier reported a somewhat weaker outburst (IAUC 5900) where the spectrum peaked with 590 mJy at 5 GHz while it normally showed emission of only a few mJy or even less (Mirabel et al. 1994, IAUC 5773, 5830). Hence $L_{\rm disk} \sim 3 \cdot 10^{38}$ (MR94) and $F_{5\ \rm GHz} \sim 655$ mJy seem to be reasonable numbers to describe GRS 1915+105 in an outburst state. In its lowest state GRS 1915+105 showed an apparently flat (or inverted) spectrum with as flux as low as 0.2 mJy at 3.6 cm on April 27, 1993 (IAUC 5830) while the X-ray flux was even somewhat brighter than in March 1994 (Brandt et al. 1993, IAUC 5779; Sazonov et al. 1994, IAUC 5959). We adopted a distance of 12.5 kpc.

GRO J1655-40 We will concentrate on the August 1994 outburst of this source which was covered by the VLBI observation and showed superluminal motion; we will adopt a distance to the source of 4 kpc (Tingay et al. 1995, Bailyn et al. 1995). The BATSE team (Zhang et al. 1994, IAUC 6046) reported an 20-200 keV x-ray luminosity of $2.5 \cdot 10^{37}$ erg/sec during the outburst, given the steep photon spectrum of ~ -3 the total x-ray luminosity must have been substantially higher and of the order $\sim 10^{38}$ erg/sec as quoted by Harmon et al. (1995) and Tingay et al. (1995).

The radio outburst started after August 12 with a 5 GHz flux of 1.1 Jy and 2.5 Jy on Aug 18. The 843 MHz flux peaked on Aug 15 at 5.5 Jy compared to 0.9 Jy on Aug 12 where the source actually showed a flat spectrum (Campbell-Wilson & Hunstead 1994, IAUC 6052, 6055 & 6062) ; Hjellming 1994, IAUC 6055 & 6060). Hence we used in Fig. 1 the flux during the flat radio spectral state. Several outbursts followed thereafter which reached similar if somewhat lower numbers (perhaps with a decreasing trend, see light curve in Hjellming & Rupen 1995). We can catch the low state of this source by looking at the situation prior to an outburst where the lowest flux levels were reached but a flat radio spectrum is detected. Such a situation occurred on Nov. 1 where the hard x-ray luminosity had decreased to less than $\sim 2 \cdot 10^{36}$ erg/sec (hence a total x-ray luminosity of $\lesssim 8 \cdot 10^{36}$ erg/sec (Zhang et al. 1994, IAUC 6101) and the radio flux to 4 mJy at 5GHz with a flat high frequency spectrum (Hjellming et al. 1994., IAUC 6107).

1E1740.7-2942 is a strong emitter of hard x-rays and was observed in two states by the russian spacecraft GRANAT on various occasions (Bouchet et al. 1991, Sunyaev et al. 1991). In its 'standard state' the luminosity in the 4-300 keV band where most of the luminosity is emitted was $L_{\rm x} = 3.2 \cdot 10^{37}$ erg/sec. There is also a hard state with an additional broad peak around 480 keV (redshifted pair annihilation?) and a report of low state with only $L_{\rm x} \sim 2 \cdot 10^{36}$ erg/sec. We only consider the normal state with luminosity $L_{\rm disk} = 2-4 \cdot 10^{37}$ erg/sec. Chen et al. (1994) also argue for an average disk luminosity of $3 \cdot 10^{37}$ erg/sec (D=8.5 kpc).

The VLA observations of Mirabel et al. (1992) showed a beautiful edge brightened extended jet structure of 1E1740.7-2942 with a central radio core possibly having a flat spectrum. Compared to the x-ray flux the source is very weak in radio and the average VLA flux of the core at 5GHz is around 0.3 mJy.

GRS 1758-258 is a persistent X-ray source in the GC with the same flux and spectrum as 1E1740.7-2942 (Churazov et al. 1994). At a distance of 8.5 kpc this corresponds to at least $2 \cdot 10^{38}$ erg/sec. VLA observations of this jet source were made by Rodriguez et al. (1992) and revealed a marginal detection of a central core with a flux of 0.2 mJy.

SS 433 This source does not quite fit into the "Hertzsprung-Russell diagram for black holes" as its primary emission component which is associated with the accretion disk does not radiate in x-rays as one would expect for the low central mass of a few solar mass (Eq.1) but in the UV as do AGN. This, however, is not too surprising if one remembers that SS 433 is in a close binary system and quite probably surrounded by a thick, supercritical accretion torus and therefore may have completely different radiation characteristics then 'normal', sub-critical thin disks. Still energy- and mass-conservation must be obeyed and we can include it into our investigation. The distance we are using is 4.85 kpc (Vermeulen et al. 1993a).

The bolometric disk luminosity of SS 433 is usually estimated to be in the range $L_{\rm disk,S433} \sim 10^{39} - 10^{40}$ erg/sec (Wagner 1986, Anthokina & Cherepashchuk 1987). The discussion of the corresponding radio data is somewhat more complicated as it requires to disentangle the various contributions of this highly variable source. Fortunately there was a large campaign dedicated to SS 433 in May/June 1987 including VLBI and multi frequency radio-photometric observations (Vermeulen et al. 1993a&b). The VLBI data show a central core with 5 GHz fluxes in the range 22-190 mJy and total fluxes between 102 and 411 mJy, from the monitoring data one finds that flat spectrum flares can reach up to 800 mJy. One might label all three contributions as coming from the core and to be consistent with all other datasets and our model we will stick with the (geometric) mean VLA core fluxes (Hjellming & Johnston 1981) as used in Paper II yielding ~ 0.35 Jy for SS 433, quite consistent with the total flux of the VLBI structure.

X-ray binaries Cyg X-1 shows a relatively constant mean radio flux with a flat spectrum around 15 mJy (Hjellming et al. 1975) and an average x-ray luminosity of $4.2 \cdot 10^{37}$ erg/sec (Liang & Nolan 1984), the variations in both bands are usually less than a factor 2.

Cyg X-2 has a low state and a flaring state roughly corresponding to 5 GHz fluxes between 0.5 mJy and 4 mJy with peaks up to 12 mJy (Hjellming et al. 1990). The x-ray luminosity is on average 10^{38} erg/sec where the variation may yield a factor 2 (Hasinger et al. 1990).

Cyg X-3 does show relativistic expansion with $v \gtrsim 0.35c$ (Geldzahler et al. 1983, Spencer et al. 1986), a high x-ray variability with a low state around 10^{37} erg/sec and a high state with up to 10^{38} erg/sec (Watanabe et al. 1994). There seems to be a correlation between the x-ray flares and strong radio outbursts which may reach fluxes up to 10 Jy and average around 1 Jy, while the quiescence level is around 100 mJy (using a flat spectral index).

Sco X-1 again shows an x-ray variability of a factor 2, with an average x-ray luminosity of $\sim 10^{37}$ erg/sec (e.g. Hasinger 1987) at an adopted distance of 500 pc. The VLA radio core flux is around 1 mJy in the low state while the high state is between 10-20 mJy (Geldzahler & Formalont 1986). There is a correlation between x-ray and radio flaring (Hjellming et al. 1990).

Circinus X-1 is one of the more puzzling x-ray binaries, high resolution maps show a curved two-sided jet structure (Stewart et al. 1993). Here we will refer to a simultaneous radio/x-ray observation (Stewart et al. 1991) where the radio flux was of the order of 5 mJy but seemed to have decreased in recent years (Stewart et al. 1993). For the 1989 epoch the x-ray luminosity reached luminosities of $0.5 - 1.5 \cdot 10^{38}$erg/sec for a distance of 6.5 kpc (Stewart et al. 1993) and peak radio fluxes around 5 mJy. Peak radio fluxes at a much higher level have been observed in the past with signs for a declining level of activity (27 flares with 300-1000 mJy in 1978/81 down to only five 100 mJy flares in 1988/89. For lack of simultaneous data, we have not included those in our diagram and only discuss them shortly in the main body of the text. The same is true for the x-ray low-state.

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