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Blazars in Low-Luminosity and Radio-Weak AGN?

Heino Falcke, Sera Markoff, Peter L. Biermann

Max-Planck-Institut für Radioastronomie, Auf dem Hügel, D-53121 Bonn, Germany

Abstract. Typical blazars seem to be associated with FR I and FR II radio galaxies and radio-loud quasars. However, what happens at lower powers? Do blazars exist in low-luminosity AGN or do they exist in radio-quiet AGN? Our recent detection of superluminal motion in a supposedly radio-quiet Seyfert raises the question whether beaming can play an important role in some of these objects as well. Moreover, VLBI observations of nearby low-luminosity AGN reveal compact flat-spectrum radio cores very similar to those in bright radio-loud blazars. Furthermore, with the detection of X-ray emission from the least luminous AGN we can study, Sgr A* in the Galactic Center, this source seems to be dominated entirely by non-thermal emission – like in BL Lacs. The same may be true for some X-ray binaries in the Low/Hard-state. Inclusion of low-power radio jets into the overall picture provides some clues for what type of accretion is important, what the power, radiative efficiency and matter-content of jets is, and what mechanism could be responsible for making jets radio-loud. We specifically discuss whether proton-proton collisions in a hot accretion flow could provide the switch for the radio-dichotomy.

1. Introduction

Over the last decades our basic picture of what blazars are has solidified. It is not even discussed anymore that the cause of the blazar and BL Lac phenomenon are relativistic jets and their non-thermal emission. In many cases this jet emission dominates the spectrum of these sources over the entire electromagnetic spectrum – from radio through TeV. The main discussions today revolve mainly around the internal structure and parameters of the jets, and the particle processes responsible for the emission.

Within the blazar community we have become so accustomed to jets that we take them for granted, however, outside the community jets are still considered something exotic: one tries to get away with thermal, spherical or disk-only models as long as possible. One example certainly is the Gamma-Ray Burst (GRB) field. This are the most violent, non-thermal events we know in the universe. After all the experience with the history of AGN research, it should have been natural to start with the assumption that these energetic sources have a setting similar to the other violent sources we know in the universe – blazar jets. Still, only after many years and under the overwhelming weight of extremely luminous GRBs like GRB971214, the fireball model collapsed into various jet models (one of which was developed by us and which we cannot resist to reference, i.e. Pugliese, Falcke, & Biermann 1999).

Another example are X-ray binaries, which are considered micro-quasars (Mirabel & Rodríguez 1999) and where many jets have been observed (Fender & Hendry 2000; Fender & Kuulkers 2000). However, so far we have not identified anything similar to a blazar or BL Lac in this field, and most emission models seem to ignore completely the non-thermal jet component. Is this justified in all cases?

Finally, we need to mention the AGN-field itself. Clearly, blazars are just the tip of the iceberg since we usually are only looking at the most luminous AGN. Only some 10% of these can be considered radio-loud, and of these only a small fraction will point towards us to reveal the amplified non-thermal spectrum through boosting. Of course there are many more AGN around: radio-quiet quasars and low-luminosity AGN that we never really consider to be blazars or blazar-like, yet even here jets are important ingredients.

Thus, the question we want to address is: can we identify blazars or blazar-like sources in other classes of astrophysical sources? How do we find them and what are we looking for? In the end this boils down to the question what the definition of a blazar actually is. Does "blazar" in this context imply an observational classification or a description of a physical state? For example, in luminous AGN relativistic boosting is very important since it makes it possible for the non-thermal emission to dominate over any thermal emission. But what happens if for some reason the thermal emission is strongly suppressed anyway, e.g. by a hot, radiatively inefficient accretion flow? In this case we will still see the non-thermal jet emission dominating even from large angles of the line-of-sight to the jet axis and we may still have substantial variability – do we call this a blazar even without relativistic boosting being important? And if not, how are we going to tell such a source apart from a boosted jet in surveys? Determining the Doppler factor of jets is still very difficult.

Rather than answering all these question here, we will rather discuss a few recent observational results on non-traditional blazars sources, that nevertheless show how difficult such a classification can become. Since some of the distinctions among AGN are related to the question of radio-loudness we will also discuss this issue here, since it was hotly debated at this workshop.

2. Radio Dichotomy

The first quasars were actually discovered through their radio identification (Hazard, Mackey, & Shimmins 1963) and belonged to the blazar class. It was soon found that many other quasars (QSOs) exist that do not show such strong radio emission. Indeed, support for a bimodal distribution of radio luminosities (relative to optical luminosity) came from radio observations of optically (Strittmatter et al. 1980; Kellermann et al. 1989; Falcke, Sherwood, & Patnaik 1996) and X-ray selected quasar samples (della Ceca et al. 1994). In some cases with lower statistics the evidence for an actual bimodality remained ambiguous (Hooper et al. 1996) and White (this conference, see also Helfand et al. 1999) claimed that in the (radio-selected) FIRST quasar survey a bimodality was not confirmed. Similarly, at this conference Meg Urry raised the question whether in fact there is a continuous distribution of radio-to-optical luminosities rather than a dichotomy. Are we fooled similar to the apparently artificial distinction between X-ray and radio-selected BL Lacs that is now becoming replaced by a continuum of sources just peaking at different frequencies?

The answer to this challenge is probably that both camps are not entirely wrong, depending on what the actual question is. The problem is, that any dichotomy in the physics of AGN and of jet formation can be easily washed out by various effects. A survey that contains a mixed bag of AGN – old and young, luminous and faint, obscured and face on – may in fact not show any bimodality while the underlying physics still is. Why is this?

The dichotomy is seen so far mainly in optically selected samples of quasars with rather homogeneous properties: strong and luminous UV bump and broad emission lines. Assuming this is indeed emission from radiatively efficient accretion disks, the optical luminosity should be a good measure of the accretion power onto the central black hole. Similarly, if the radio properties of quasars are homogeneous then the radio-luminosity can be a useful estimate for the jet power. A constant radio-to-optical flux density ratio (the R-parameter) then reflects nothing else but a constant fraction of the accretion power being channeled into a jet. This is one of the motivations behind the jet-disk symbiosis idea (Falcke & Biermann 1995) and explains the radio optical correlations of quasars (Baum & Heckman 1989; Miller, Rawlings, & Saunders 1993; Falcke, Malkan, & Biermann 1995). A bimodality in the R-parameter than implies a dichotomy in the jet formation – whatever that mechanism is.

On the other hand the R-parameter is a rather shaky measure for such a physical effect. First of all, the radiative efficiency of jets need not be constant and in fact depends on many external factors. Doppler boosting of the core certainly affects it, and for hotspots the pressure of the surrounding medium and their location of the jet terminus (inside or outside the galaxy) can change the radio output quite strongly for a fixed jet power. The latter is seen for example in the declining radio power for jets as they grow from GPS (Gigahertz-Peaked-Spectrum) to CSS (Compact-Steep-Spectrum) sources and finally evolve into large radio galaxies (e.g., O'Dea 1998).

On the other hand, the optical luminosity can easily be obscured or could be entirely absent so that a reliable estimate of the accretion power is not possible. The optical selection of the PG quasar sample, on which many of the papers mentioned above are based on, seemed to have avoided many of these problems. In this context "bias" can be good since it provides one with a rather clean sample that gives us some insight into the physics of jet formation. This is illustrated in Figure 1 where we show the distribution of R-parameters in the PG quasar sample, however, with all known flat-spectrum ($\alpha > -0.5$ at 5 GHz) sources taken out – this discriminates strongly against those quasars affected by boosting and also against GPS sources. The resulting distribution is rather clean and bimodal (but is also present if one does not take out the flat-spectrum quasars).

The answer to the question whether jet formation in luminous quasars is bimodal, is therefore most likely "yes". On the other hand, the question whether

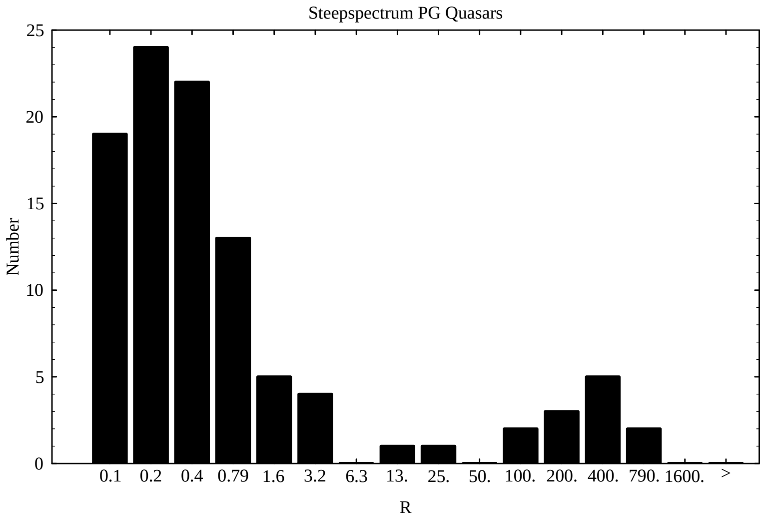

Figure 1. Distribution of the radio-to-optical flux density ratio R for steep-spectrum PG-quasars (from Falcke, Sherwood, Patnaik 1996)

the R-parameter distribution for 'all the AGN on the sky' is bimodal, is most likely "no".

3. Radio-Quiet Quasars & Seyferts

One interesting finding from studying the R-parameter distribution in PG quasars was that the region intermediate between the radio-loud and radio-quiet distribution was not empty but populated with many flat-spectrum sources (Miller, Rawlings, & Saunders 1993; Falcke, Malkan, & Biermann 1995; Falcke, Sherwood, & Patnaik 1996), called radio-intermediate quasars (RIQs). Some of these sources had radio properties similar to those of blazars: core-dominated, flat-spectrum, and variable. The suggestion was that they constitute a population of relativistically boosted radio-quiet quasars, i.e. something one might call radio-weak blazars.

To make this case watertight one would have liked to see superluminal motion in these sources. Early VLBI observations did not reveal anything but a compact core. However, one of the galaxies, III Zw 2, then became target of a monitoring campaign during a major outburst starting in 1997. Barely resolved in the first three epochs it suddenly started to expand for a brief period of about a few months (Brunthaler et al. 2000b) and then held steady while continuing to decrease in flux (Fig. 2). The spectral evolution monitored with the VLA indicated that the expansion happened on an even shorter time scale and depending on which timescale one takes the implied expansion speed was between 1.2 and 2.7 c, i.e. superluminal even in the most conservative case.

This finding is interesting, since it shows that indeed the RIQs contain relativistic jets. Apart from the bright radio core, III Zw 2 has all the properties of a Seyfert galaxy with a spiral host and very faint, uncollimated, and short radio lobes – certainly not an FR I or FR II radio galaxy. Is this then a radio-

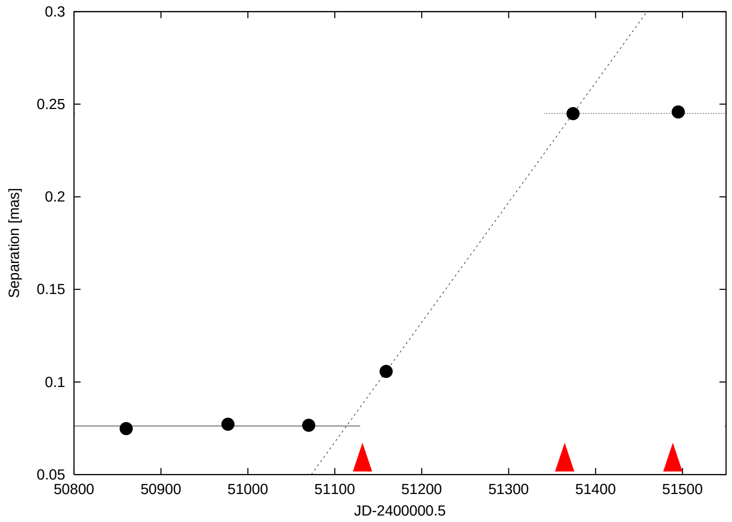

Figure 2. Component separation as a function of time for the Seyfert galaxyIII Zw 2 as measured by the VLBA at 43 GHz. There is a short period of superluminal expansion indicating the presence of a relativistic jet in this Seyfert galaxy. (From Brunthaler, Falcke, Bower et al. 2000)

weak blazar? It certainly has all criteria one might require: core-dominance, variability, and superluminal motion. However, there is one additional factor complicating things: the evolution of the outburst – with a stop and go behavior – suggests that the jet itself is strongly interacting with the surrounding ISM. (Brunthaler et al. 2000a) suggest that this could be explained with an 'inflating balloon' model and the formation of ultra-compact hotspots in this galaxy, similar, yet smaller in size, to those seen in GPS and CSS sources.

Consequently the large radio flux and compact size is not entirely due to boosting alone even though a relativistic jet is clearly present. Here we may be pointed also into another direction, if III Zw 2 can be regarded as a luminous and perhaps extreme case of a Seyfert galaxy – i.e., a supposedly radio quiet AGN. Like in radio-loud quasars, the jet might start out relativistically but then is disrupted already on the sub-parsec scale, possibly interacting with the torus in some cases, and then propagates outwards sub-relativistically as seen on parsec-scales with VLBI (Ulvestad et al. 1998; Roy et al. 2000) forming the characteristic uncollimated Seyfert radio lobes (Ulvestad & Wilson 1989). The denser ISM in spirals compared to ellipticals may play a role here.

Whether or not the jet-ISM interaction in III Zw 2 is important, the relativistic jet suggests that blazar-like radio-quiets should be detectable, possibly at rather high radio-frequencies. A few attempts to find them with the VLBA are underway (Blundell & Beasley 1998). An alternative way to look for radio-weak blazars is to do variability studies. Recently Barvainis et al. (in prep., see also Falcke et al. 2001) made multi-epoch (11 epochs) observations with the VLA of a sample of 30 radio-quiet, radio-intermediate, and radio-quiet quasars at 8.5 GHz. They found up to 20% variability within one year in the cores of radio-quiet and radio-intermediate quasars exceeding that of cores in (non-blazar) radio-loud quasars. Even among a sample of ill-selected core-dominated radio-sources (used as phase-calibrators but dominated by blazars) only a few sources showed somewhat more variability on the same timescale. Clearly, the compact radio-emission in these variable radio-quiet/intermediate quasars is AGN-dominated and most likely from a jet. It would be worth investigating some of the top variability performers (after III Zw 2 which tops that list in this survey) in greater detail with the VLBA to look for jets and superluminal motion again.

4. Low-Luminosity AGN

Of course, blazars could be dim not only because they are radio-weak, but also because the jet power and the accretion rate onto the black hole are low. Blazars and BL Lacs have been associated with both FR I and FR II radio galaxies (Urry & Padovani 1995) and hence span a large range of luminosities and jet powers already. Does this continue further down to even less luminous AGN? Marcha et al. (1996) studied a sample of fainter core-dominated AGN and found a number of blazar-like sources, however, with a large spread in optical and line-emission properties that makes it once more difficult to decide what to call a BL Lac. Clearly, once the power is very low, emission from the galaxy – hot gas and stars – will dilute every blazar spectrum.

This saga continues at even lower powers. Nagar et al. (2000), Falcke et al. (2000b), and Falcke et al. (2000a) studied a sample of Low-Luminosity AGN (LLAGN), selected from the spectroscopic survey of Ho, Filippenko, & Sargent (1995) with the VLA and the VLBA. A large fraction of these AGN showed flat-spectrum compact radio cores in their nuclei. In the brightest cores the VLBA resolved the radio emission into jet-like structures. Morphology and spectral index together therefore suggest that the compact radio emission, like in radio-loud and radio-quiet quasars, is produced in an outflow rather than in an advection dominated accretion flow (ADAF, e.g. Yi & Boughn 1998). Finally, a comparison of the radio flux densities at several epochs revealed rather strong intra-year variability with peak-to-peak variations of up to 200-300% in some cases. X-ray emission is also detected in many of these LLAGN (Terashima, Ho, & Ptak 2000) as are optical/UV continuum point sources (Maoz et al. 1995). Of course, the UV-to-X-ray emission might come from an accretion disk, as commonly assumed, but how can we be sure? Could some of it also be non-thermal emission from a relativistic jet pointing towards us? How could we possibly pick out a very weak BL Lac from a 'normal' source?

This confusion is highlighted in Fig. 3 where we show the radio-optical correlation for a mixed sample of radio-loud AGN together with the predictions from the jet-disk symbiosis model from Falcke & Biermann (1996) outlining regions of constant inclination angle to guide the eye. Besides an overall scaling of the radio core power with optical emission it is interesting that the radio cores of giant elliptical LLAGNs seem to connect to the radio cores in FR I radio galaxies. They are also close to the "blazar" line (solid) and are slightly offset from the rest of the LLAGN population. It is not clear at present, whether this represents another radio-loudness dichotomy at lower luminosities or not. There is some evidence that FR Is are simply underluminous in emission lines (Zirbel &

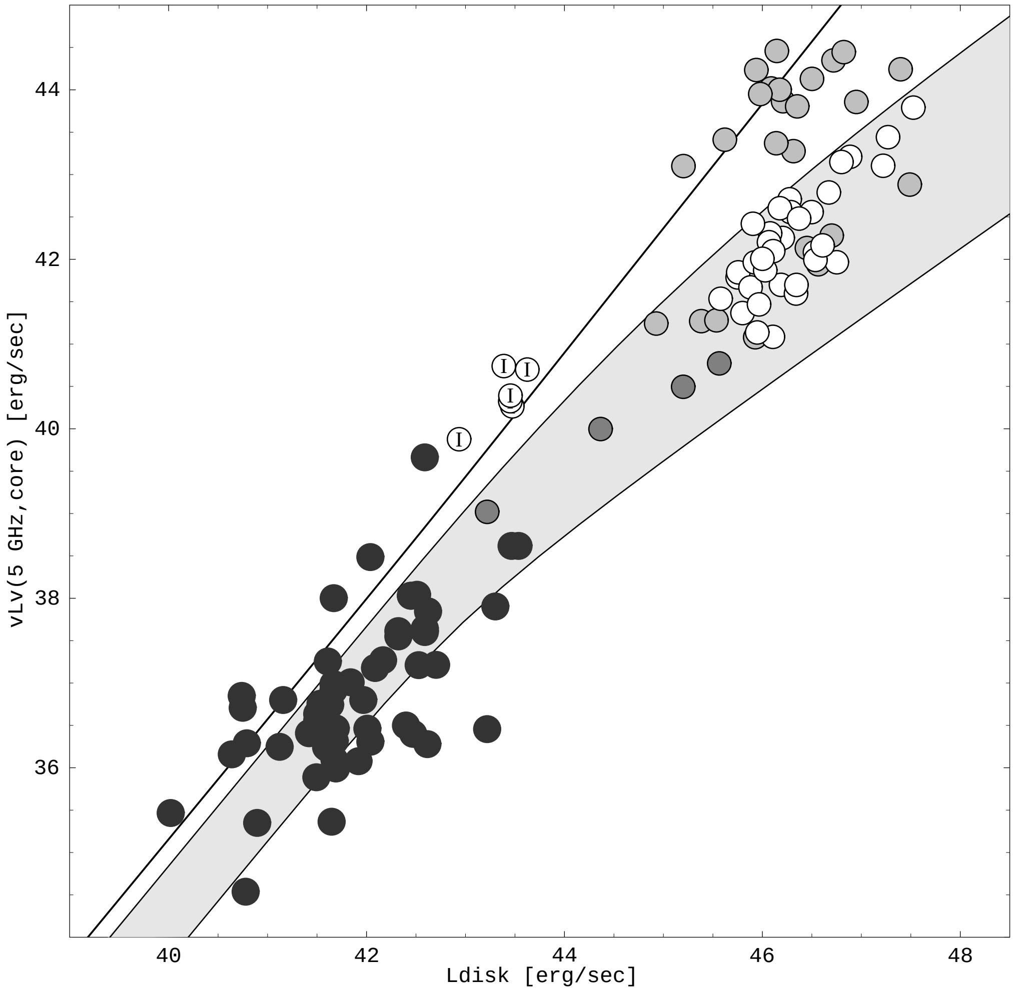

Figure 3. 5 GHz radio core vs. bolometric nuclear luminosity (derived from narrow Hα luminosities) for radio-loud AGN as given in Falcke, Malkan, Biermann (1995) and Falcke (1996). Solid black dots are LLAGN from Falcke, Nagar, Wilson (2000). Circles marked "I" are FR I radio galaxies from Rawlings & Saunders (1991), open circles are quasars. Gray shades indicate flat-spectrum, core-dominated quasars, dark gray shades are radio-intermediate quasars and Seyferts. The lines are the radio-loud jet-disk symbiosis model from Falcke & Biermann (1996), where the thick line represents sources with inclination angles at the boosting cone, i.e. what is expected for blazars. Interestingly the LLAGN at this line (black dots) are all giant ellipticals and seem to connect to FR I radio galaxies. These sources may be underluminous in Hα (i.e. $L_{\rm disk}$) emission and might need to be shifted to the right.

Baum 1995), perhaps due to obscuration (Falcke, Gopal-Krishna, & Biermann 1995, but see Chiaberge, Capetti, & Celotti 2000) or due to radiatively deficient disks. This would shift the entire population to the right and thus below the "blazar" line.

Clearly the FR Is and their low-luminosity siblings cannot be all blazars in the sense that they are all pointing towards us. On the other hand Chiaberge, Capetti, & Celotti (2000) (also at this workshop) argue convincingly that if an optical point source is found in an FR I radio galaxy it is probably non-thermal synchrotron emission. Therefore these sources may be dominated by non-thermal emission but perhaps are not "blazing". In line with the BL Lac/FR I unification scheme one should still also find some sources that are well above the "blazar" line shown in Fig. 3 because of strong relativistic boosting and suppression of Hα emission. So far the sample sizes for LLAGN are probably too small to find such sources but some of them might have been included in the Marcha et al. (1996) survey.

5. Sgr A* and the nature of the radio-dichotomy

In our journey to lower luminosities we now want to take a brief look at the least luminous AGN we know of, and which may offer some clues for the physics of jets and blazars. Sgr A* is now generally believed to be the central black hole of the Galaxy and its emission mechanism has been strongly debated (see Melia & Falcke 2001 for a review). However, recent X-ray observations have provided some interesting new insight. Baganoff et al. (2000) detected a point source at the position of Sgr A* with Chandra, however, with a rather soft spectrum – too soft for thermal bremsstrahlung. On the other hand this X-ray spectrum fits nicely with the expectations one has from synchrotron self-Compton (SSC) emission from the submm-wave emission region ("submm-bump") in Sgr A*. The parameters of this bump are rather well-constrained (Falcke 1996b; Beckert & Duschl 1997) and hence calculating SSC emission is straight forward. In fact the entire radio-through-X-ray spectrum of Sgr A* is now very well fit by pure non-thermal emission from a radio jet (Falcke & Markoff 2000), the main SSC contribution coming from the nozzle.

As one can see from the model fit to Sgr A* in Fig. 4 that the spectrum up to X-rays can be explained by two humps (radio and SSC), very similar to what is seen in BL Lacs (Fossati et al. 1998). The absence of any thermal emission component provides another similarity. A major and interesting difference, however, is the fact that Sgr A* does not show an optically thin power-law at high frequencies: the strong IR limits require an almost exponential cut-off of the synchrotron spectrum. The absence of such an electron power-law also explains the compactness of the jet (as seen also in M81; Bietenholz, Bartel, & Rupen (2000)), since, in contrast to the flat-spectrum core which is the compact $\tau = 1$ surface of the jet, the extended jet emission in AGN is always optically thin, steep-spectrum emission from a power-law.

In Sgr A* we are very confident that the highest synchrotron frequencies come from the smallest region, just a few Schwarzschild radii from the black hole (e.g., Krichbaum et al. 1998). Hence, the electron population we see in Sgr A* is probably the freshly injected particle population at the base of the jet and the

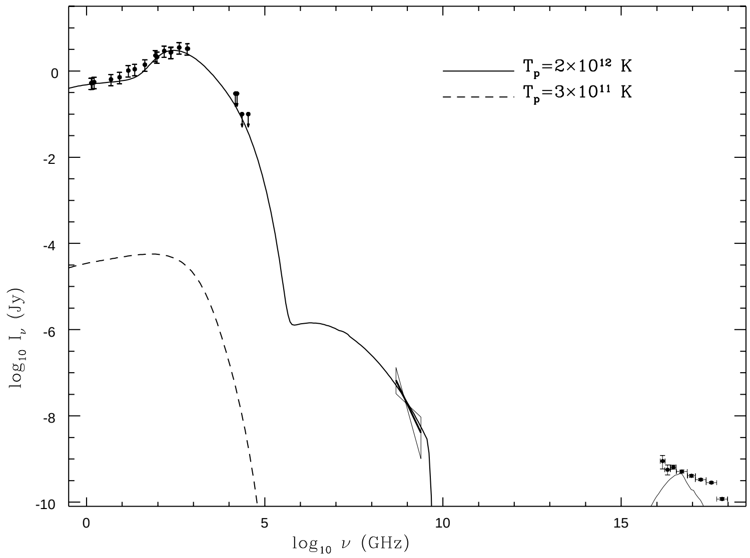

Figure 4. Radio through γ-ray spectrum for Sgr A* resulting from proton-induced $e^{\pm}$'s in a hot ($T_p = 2 \cdot 10^{12}$ K) accretion flow fed into a plasma jet. This includes radio emission from jet and nozzle, X-ray emission via synchrotron self-Compton in the jet, and γ-rays from π^0-decay in the accretion flow. The γ-ray data are considered upper limits because of the large beam of the observations. The fitted parameters for the jet are: nozzle width $2r_0 \sim 5 \cdot 10^{12}$ cm, height $z_0/r_0 = 8$, inclination angle of jet with respect to line-of-sight $\theta_i = 23°$, and $B_0 =$ 20 G (implying an equipartition factor of $k = 0.2$, i.e., magnetically dominated). The fit is very tightly constrained and the remaining free parameters given here have an inherent scale, i.e. gravitational radius or equipartition value. The dashed line shows the spectrum for the same parameters but with $T_p = 3 \cdot 10^{11}$ K.

inner region of the accretion flow *before* the particles are redistributed by shock acceleration. Therefore Sgr A* may offer a unique perspective into jet formation and particle acceleration. From the frequency of the SSC peak relative to the synchrotron peak and the shape of the submm-bum one can then directly derive that the characteristic electron Lorentz factor has to be around $\gamma_e \sim 10^2$. This fits nicely expectations for the minimum Lorentz factor of electrons in radio-loud quasar jets and hence also in blazars (Celotti & Fabian 1993; Falcke & Biermann 1995).

One can then ask what creates these particles at the base of the jet? The best explanation for the absence of a thermal bump in the Sgr A* spectrum is a hot, optically thin accretion flow (Rees 1982; Melia 1992; Narayan et al. 1998) and some of the synchrotron emission in the jet could come from the hot electrons near the inner edge of the accretion disk being advected in a jet. An alternative proposal (Markoff, Falcke, & Biermann 2000) is that proton-proton collisions could be responsible. As soon as the protons in the flow reach a threshold temperature around 10^{12} K, *pp*-collisions become inelastic and inevitably produce pairs, neutrinos, and γ-rays in hadronic cascades. The resulting electron/positron pair-spectrum peaks around 30 MeV, essentially what is needed for Sgr A*. The pair-production rate is a function of the accretion rate and the viscosity parameter α of the accretion flow. For the parameters of Sgr A*, the right number of pairs is produced for accretion rates of order $\alpha^{-1}\dot{M} \sim 10^{-4} M_{\odot}$ yr^{-1}, just what is expected from Bondi-Hoyle accretion of stellar winds.

The spectrum from this process in conjunction with a jet model is what is actually shown in Fig. 4. It also includes the expected γ-emission from the pion-decay. What makes the *pp*-process so interesting is that it drops drastically when the temperature falls below 10^{12} K. This is the case at the inner edge of hot accretion flows when one reduces the spin of the black hole (e.g., (Manmoto 2000)). As a consequence the jet quickly switches to a "radio-quiet" state when the spin drops below maximal (dashed line in Figure 4). Hence, *pp*-collisions are an interesting mechanism for particle injection into jets, naturally providing a fundamental switch between radio-loud and radio-quiet jets, and establishing a link between black hole spin and radio-loudness.

In this picture radio-loud jets would be a mixture of a pair plasma and a normal plasma and require hot accretion flows around maximally spinning black holes. The difference in accretion disk structure in radio-loud/radio-quiet AGN could be reflected in their X-ray spectra as reported by Eracleous, Sambruna, & Mushotzky (2000).

6. Summary

Let us now summarize the findings of our exploration into the non-blazar space. First we need to define what we actually mean by BL Lac or blazar-like when applying these terms to weaker sources. The main feature of BL Lacs is their dominant non-thermal broadband spectrum. Domination here needs to be taken relative to other emission components from the *black hole system*, such as the thermal emission from the accretion flow, and not, e.g., relative to the host galaxy. This means that classifications based on ground-based spectroscopy (break contrast, equivalent width) will loose their usefulness for low AGN luminosity levels (Marcha et al. 1996).

Relativistic boosting is another important feature that characterizes a luminous blazar. It mainly serves to enhance the non-thermal over the more isotropic thermal emission. If, however, the thermal emission is suppressed by other means, boosting may not be so important anymore. The physics inside the jet, particle acceleration and non-thermal emission mechanisms, will remain the same with or without boosting. In fact from viewing BL Lacs or blazars at different angles and studying them at different power levels and in different environments we may have yet a lot to learn about them.

To account for these two different definitions, that may not necessarily always go together, we have tentatively started to use the word low-luminosity BL Lac in cases where we mean "non-thermal dominance" and the word low-luminosity or radio-weak "blazar" when talking about boosting.

So, where are the low-luminosity BL Lacs and blazars? In radio-quiet quasars we have now some good evidence for relativistic jets – the variability and the superluminal motion. This clearly speaks for the presence of radio-weak blazars in some of them, such as III Zw 2. They will, however, hardly ever appear as BL Lacs, since even if boosted the non-thermal emission cannot overwhelm the accretion disk emission that is always there.

On the contrary, we find a number of BL Lac-like sources in the cores of low-luminosity AGN, such as LINERS, with core dominance and strong variability. In many cases thermal X-rays are very weak, e.g. in some ellipticals (Mushotzky, priv. comm.) and it could well be that the non-thermal emission is the most important. So, they can look like BL Lacs without necessarily being boosted. This is probably what is seen in Sgr A* in the Galactic Center and hence we might call it the least luminous BL Lac.

Finally, we want to mention that another interesting direction to look in, for future studies, are X-ray binaries. Especially in the Low/Hard-state, X-ray binaries seem to have very little thermal emission and show a flat spectrum emission that extends from radio to optical and then continues in an X-ray power-law. In trying to fit the broadband spectrum of the newly discovered X-ray binary XTE J1118+480 we were able to account for the entire spectrum from radio to X-rays by emission from a mildly relativistic jet (Markoff, Falcke, & Fender 2000) alone. The question to be asked therefore is whether this actually is the BL Lac analogue for stellar mass black holes.

References

Baganoff, F., Bautz, M., Brandt, N., Cui, W., Doty, J., Feigelson, E., Garmire, G., Maeda, Y., Morris, M., Pravdo, S., Ricker, G., & Townsley, L. 2000, ApJ, submitted

Baum, S. A., & Heckman, T. 1989, ApJ, 336, 702

Beckert, T., & Duschl, W. J. 1997, A&A, 328, 95

Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2000, ApJ, 532, 895

Blundell, K. M., & Beasley, A. J. 1998, MNRAS, 299, 165

Brunthaler, A., Falcke, H., Bower, G. C., Aller, M. F., Aller, H. D., & Teräsranta, H. 2000a, in Proceedings of the 5th EVN Symposium (Gothenburg, Sweden: Onsala Space Observatory, Chalmers Technical University), in press

Brunthaler, A., Falcke, H., Bower, G. C., Aller, M. F., Aller, H. D., Teräsranta, H., Lobanov, A. P., Krichbaum, T. P., & Patnaik, A. R. 2000b, A&A, 357, L45

Celotti, A., & Fabian, A. C. 1993, MNRAS, 264, 228

Chiaberge, M., Capetti, A., & Celotti, A. 2000, A&A, 355, 873

della Ceca, R., Lamorani, G., Maccacaro, T., Wolter, A., Griffiths, R., Stocke, J. T., & Setti, G. 1994, ApJ, 430, 533

Eracleous, M., Sambruna, R., & Mushotzky, R. F. 2000, ApJ, 537, 654

Falcke, H. 1996a, in ASP Conf. Ser., Vol. 102, The Galactic Center (San Francisco: Astronomical Society of the Pacific), 453

Falcke, H. 1996b, in IAU Symp. 169: Unsolved Problems of the Milky Way, Vol. 169, 169

Falcke, H., & Biermann, P. L. 1995, A&A, 293, 665

Falcke, H., & Biermann, P. L. 1996, A&A, 308, 321

Falcke, H., Gopal-Krishna, & Biermann, P. L. 1995, A&A, 298, 395

Falcke, H., Lehár, J., Barvainis, R., Nagar, N., & A.S., W. 2001, in Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring, ASP Conf. Ser. (San Francisco: Astronomical Society of the Pacific), in press

Falcke, H., Malkan, M. A., & Biermann, P. L. 1995, A&A, 298, 375

Falcke, H., & Markoff, S. 2000, A&A, 362, 113

Falcke, H., Nagar, N. M., Wilson, A. S., & Ulvestad, J. S. 2000a, in Black Holes in Binaries and Galactic Nuclei, ESO Workshop, ed. P. W. L. Kaper, E.P.J. van den Heuvel (Springer Verlag), in press

Falcke, H., Nagar, N. M., Wilson, A. S., & Ulvestad, J. S. 2000b, ApJ, 542, 197

Falcke, H., Sherwood, W., & Patnaik, A. R. 1996, ApJ, 471, 106

Fender, R. P., & Hendry, M. A. 2000, MNRAS, 317, 1

Fender, R. P., & Kuulkers, M. A. 2000, MNRAS, submitted

Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433

Hazard, C., Mackey, M. B., & Shimmins, A. J. 1963, Nature, 197, 1037

Helfand, D. J., Becker, R. H., Gregg, M. D., Laurent-Muehleisen, S., Brotherton, M., & White, R. L. 1999, in American Astronomical Society Meeting, Vol. 195, 1701

Ho, L. C., Filippenko, A. V., & Sargent, W. L. 1995, ApJS, 98, 477

Hooper, E. J., Impey, C. D., Foltz, C. B., & Hewett, P. C. 1996, ApJ, 473, 746

Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, AJ, 98, 1195

Krichbaum, T. P., Graham, D. A., Witzel, A., Greve, A., Wink, J. E., Grewing, M., Colomer, F., de Vicente, P., Gomez-Gonzalez, J., Baudry, A., & Zensus, J. A. 1998, A&A, 335, L106

Manmoto, T. 2000, ApJ, 534, 734

Maoz, D., Filippenko, A. V., Ho, L. C., Rix, H., Bahcall, J. N., Schneider, D. P., & Macchetto, F. D. 1995, ApJ, 440, 91

Marcha, M. J. M., Browne, I. W. A., Impey, C. D., & Smith, P. S. 1996, MNRAS, 281, 425

Markoff, S., Falcke, H., & Biermann, P. L. 2000, in preparation

Markoff, S., Falcke, H., & Fender, R. 2000, ApJ, submitted

Melia, F. 1992, ApJ, 387, L25

Melia, F., & Falcke, H. 2001, ARA&A, 39, submitted

Miller, P., Rawlings, S., & Saunders, R. 1993, MNRAS, 263, 425

Mirabel, I. F., & Rodríguez, L. F. 1999, ARA&A, 37, 409

Nagar, N. M., Falcke, H., Wilson, A. S., & Ho, L. C. 2000, ApJ, 542, 186

Narayan, R., Mahadevan, R., Grindlay, J. E., Popham, R. G., & Gammie, C. 1998, ApJ, 492, 554

O'Dea, C. P. 1998, PASP, 110, 493

Pugliese, G., Falcke, H., & Biermann, P. L. 1999, A&A, 344, L37

Rawlings, S., & Saunders, R. 1991, Nature, 349, 138

Rees, M. J. 1982, in AIP Conf. Proc. 83: The Galactic Center, 166

Roy, A., Wilson, A., Ulvestad, J., & Colbert, E. 2000, in Proceedings of the 5th EVN Symposium (Gothenburg, Sweden: Onsala Space Observatory, Chalmers Technical University), in press

Strittmatter, P. A., Hill, P., Pauliny-Toth, I. I. K., Steppe, H., & Witzel, A. 1980, A&A, 88, L12

Terashima, Y., Ho, L. C., & Ptak, A. F. 2000, ApJ, 539, 161

Ulvestad, J. S., & Wilson, A. S. 1989, ApJ, 343, 659

Ulvestad, J. S., Wrobel, J. M., Roy, A. L., Wilson, A. S., Falcke, H., Krichbaum, T., Bower, G., & Zensus, A. 1998, in American Astronomical Society Meeting, Vol. 193, 9003

Urry, C. M., & Padovani, P. 1995, PASP, 107, 803

Yi, I., & Boughn, S. P. 1998, ApJ, 499, 198

Zirbel, E. L., & Baum, S. A. 1995, ApJ, 448, 521