Jets in AGN – New Results from HST and VLA

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Abstract

This paper summarizes some of our recent projects which try to illuminate the nature and importance of jets associated with active nuclei and compact objects. After a short introduction on jets in radio galaxies and radio loud quasars the paper focuses on jets in other source types, such as radio-quiet quasars, Seyfert and LINER galaxies, and stellar mass black holes. Radio observations of quasars, for example, have brought new evidence for the existence of relativistic jets in radio quiet quasars, while HST and VLA observations of Seyfert galaxies have now clearly established not only the presence of radio jets, but also the great importance these jets have for the morphology and the excitation of the emission line region in these AGN. Moreover, a recent VLA survey found a large fraction of low-luminosity AGN to host compact, flat-spectrum radio cores indicating the presence of radio jets there as well. Finally the jet/disk-symbiosis model, which successfully explains radio cores in LINER galaxies, is applied to the stellar mass black hole GRS 1915+105, indicating that the radio cores in both types of sources are just different sides of the same coin. The conclusion drawn from all these observations is that radio jets are a ubiquitous feature of most—if not all—AGN and play an important effect in the overall energy budget, as well as for the interpretation of observations in other wavebands (e.g. optical emission lines).

1 Introduction

One of the main subjects for radio astronomers has been the study of extragalactic radio jets. When observed at a higher resolution many of the first radio sources which were discovered in the early years of radio astronomy later turned out to be powerful, collimated plasma flows of relativistic plasma (jets) which were ejected from the nucleus of giant elliptical galaxies. These structures can reach sizes of several million light years and hence extend way beyond their host galaxies into the vastness of intergalactic space. This relative isolation is ideal to study the physics of astrophysical plasma flows in great detail (see e.g. Bridle & Perley 1984, Bridle et al. 1994, Marti et al. 1997) and allows to make some estimates of the properties of the IGM (inter-galactic medium, e.g. Subrahmanyan & Saripalli 1993). An even more important aspect of radio jets, however, is that they are the most visible sign, the "smoking gun" so to speak, of Active Galactic Nuclei (AGN) which are thought to be powered by accreting black holes. Hence, jets have been studied with great interest over many years and a huge zoo of different jet species has emerged which will be discussed as a useful background for the further discussion in the next section.

2 Jet zoology

The main characteristics of radio jets, are the size (compact, i.e. parsec to kiloparsec scale, or extended, i.e. tens to hundreds of kiloparsecs), and the spectral index (flat or steep) of the radio sources. Steep radio spectra ($\alpha < -0.5$, $S_\nu \propto \nu^\alpha$) are due to optically thin synchrotron emission from large, extended radio sources, while flat radio spectra can be produced if the source is very compact and the spectrum is dominated by radiation from a number of optically thick synchrotron components.

A typical powerful radio galaxy—a so called Fanaroff & Riley (1974) type II radio galaxy (short FR II)—consists of two steep-spectrum, extended lobes connected by very faint (if visible at all), well-collimated plasma beams, and a compact flat-spectrum core (which will be discussed in more detail in Sec. 5-7). FR II jets are produced by the most powerful AGN, have the largest kinetic powers of any jets observed (i.e. Rawlings & Saunders 1991), and reach the very largest sizes observed. Probably due to their huge powers FR II jets can plow with relativistic speeds through the ambient medium, self-shielded by a huge cocoon (Begelman & Cioffi 1989), until they slow down and terminate in a huge shock—the hot spots. Behind the shock the material disperses and at least a part of it flows back toward the galaxy it was ejected from. This can be seen on many of the beautiful high dynamic-range VLA maps made in recent years (e.g. Black et al. 1992, Leahy et al. 1997).

Such beautiful structures, however, are not the rule but rather the exception: at lower powers (and low power AGN are naturally more frequent than high power AGN) the jet morphology seems to change and FR II radio galaxies suddenly turn into FR Is, where instead of a well collimated pencil-like beam with a well-defined terminus, the jet has a larger opening angle, entrains material from the ISM (DeYoung 1993, Bicknell 1994), becomes bright, and then slowly fades along the way. Clearly, in those cases the jet is no longer independent of its environment but interacts with the ISM of the host galaxy. Initially we were only able to see the effects of this interaction on the radio jet itself, but now we can also see the other side of this coin in x-ray observations, which indicate how the radio plasma pushes against gas in the galaxy (Böhringer et al. 1993; Holloway et al. 1996; Clark et al. 1997).

Not always, however, are we so fortunate to see all details of the extended jets. If, for example, those jets happen to be seen under a very small aspect angle with respect to the line of sight, relativistic effects will become very important. Since the jet has velocities close to the speed of light in the nucleus, the emission from the flat-spectrum radio core will be boosted by the relativistic Doppler effect and for small inclination angles will become so bright that it dominates the entire radio emission, overwhelming even the bright extended lobes (even though they still can be found in high-dynamic range observations, e.g. Kollgaard et al. 1992). These galaxies appear as compact, core-dominated flat-spectrum radio galaxies, sometimes called Blazars. If observed at very high-resolution Blazars often show superluminal motion (an optical illusion caused by the relativistic motion of bright features in the jet) which is accompanied by strong flux variability down to scales of less than a day (Wagner & Witzel 1995; Zensus 1997). In addition one finds luminous high-energy emission, such as x-ray and gamma-emission (up to 10 TeV, e.g. Zweerink et al. 1997), most certainly produced by scattering processes (e-γ, p-γ, or p-p) from relativistic particles within the jet (Mannheim & Biermann 1992; Dermer & Schlickeiser 1993). In fact, for some sources most of the observed luminosity is seen in gamma-rays.

But not all compact radio galaxies are Blazars, some galaxies show steep radio spectra (at least at high frequencies), yet, instead of penetrating deep into the inter-galactic medium (IGM) as FR I and FR IIs do, they get stuck inside their host galaxies, either because they are frustrated or simply too young. These sources are called CSS (compact steep-spectrum) or GPS (Gigahertz-peaked spectrum) sources (see O'Dea 1998 for a recent review). Looked at with higher-resolution one can resolve the jets and find extended lobes on scales of several kpc (for CSS) down to hundreds of parsecs (GPS, needs VLBI) — at least some of them must be the predecessors of the large FR I and FR II radio galaxies.

The main reason why these galaxies have been studied in such detail so far is their large radio fluxes of 100mJy up to several tens of Jansky, which makes them easily accessible with current technology. Hence, when we discuss the properties of relativistic jets in AGN, we usually tend to think exclusively about those radio galaxies, radio-loud quasars, and Blazars. But is this the whole universe, or just the tip of the iceberg? In the following I will discuss a number of other classes of AGN where jets have become or will become an important issue.

3 Jets in 'radio-weak' AGN

In comparison to stellar winds it is often argued that the escape speed from the central object is an important factor that determines the terminal jet speed. If that is true and since we believe that most of the AGN are powered by a black hole one should assume that if an AGN produces a jet it should *always* be relativistic. Consequently the crucial question then becomes: Do all AGN have jets? In Falcke (1994) and Falcke & Biermann (1995) we proposed that, since black holes do not have many free parameters, AGN should be similar in their basic properties ("the universal engine", Falcke 1996a) and hence one should *ab initio* assume that all AGN, rather than only a few sub-classes, have relativistic jets. Using Occam's razor we also suggested that jets and accretion process (accretion disk) should form a symbiotic system in the sense that both are always required for an AGN. As it turned out, this hypothesis, in its simplicity, was surprisingly successful and has motivated most of the research presented here. In a review Livio (1997) comes to a similar conclusion, i.e. that a majority of accretion disk systems produce jet-like outflows, however, negates the necessity of jets for accretion disks by hinting at CVs where jets are not observed. Fortunately in a later paper (Shahbaz, Livio, Southwell, & Charles 1997) the same author is the first to report evidence for a jet-like outflow in a CV.

3.1 Radio-Quiet Quasars

One class of sources where the jet/disk-symbiosis principle was used first was the UV/radio-correlation of quasars (Falcke, Malkan, Biermann 1995). If one looks at the distribution of the radio-to-optical flux ratios (R-parameter) of an optically selected quasar sample (here the PG quasar sample) one finds a clear dichotomy between radio-loud and radio-quiet sources. This is especially true if one selects only steep-spectrum quasars, which are supposedly unaffected by orientation effects (see Fig. 1, top). VLA observations of the steep-spectrum radio-loud PG quasars (Miller, Rawlings, & Saunders 1993) and Kellermann et al. (1994) have clearly established, that they have FR II-type radio jets. The radio dichotomy was occasionally attributed to the fact that radio-quiet quasars do not show and do not have radio-jets at all. However, as we all know, 'absence of evidence is not evidence of absence' — especially not, if one has not even looked yet, and following the jet/disk-symbiosis principle, one would rather suppose that radio-quiet quasars have jets as well.

3.2 Predictions for boosted radio-quiet jets

We therefore have to ask: How can we obtain evidence for or against the presence of jets in radio quiet quasars? One direction to go would be to look for relativistic boosting. In an optically selected sample, we would expect that, if radio-quiet quasars have relativistic jets, some of these quasars are accidentally pointing towards us, thus producing a population of 'weak blazars' with the following properties:

a) similar to flat-spectrum, core-dominated, variable radio quasars but with relative low radio-to-optical flux ratio (R),

b) apparent brightness temperatures close to $\sim 10^{12}$K or above,

c) superluminal motion,

d) very faint (i.e. radio-quiet) extended radio emission,

e) number of sources in a well selected sample, and their Doppler-boosting relative to radio-quiet quasars both imply the same Lorentz factor,

f) luminosity- and z-distribution consistent with radio-quiet parent population,

g) host galaxies compatible with those of radio-quiet quasars.

This list is quite helpful, as it allows an either/or decision: if we do not find a population of weak blazars, we can exclude that relativistic jets in radio-quiet quasars exist (or one would have to invent an argument why these jets never point towards us); if we find them, we can prove that radio-quiet quasars must have relativistic jets. Interestingly, in the PG quasar sample we indeed find a population of quasars, which at least partially fulfill most of the criteria listed above and most likely are such weak blazars.

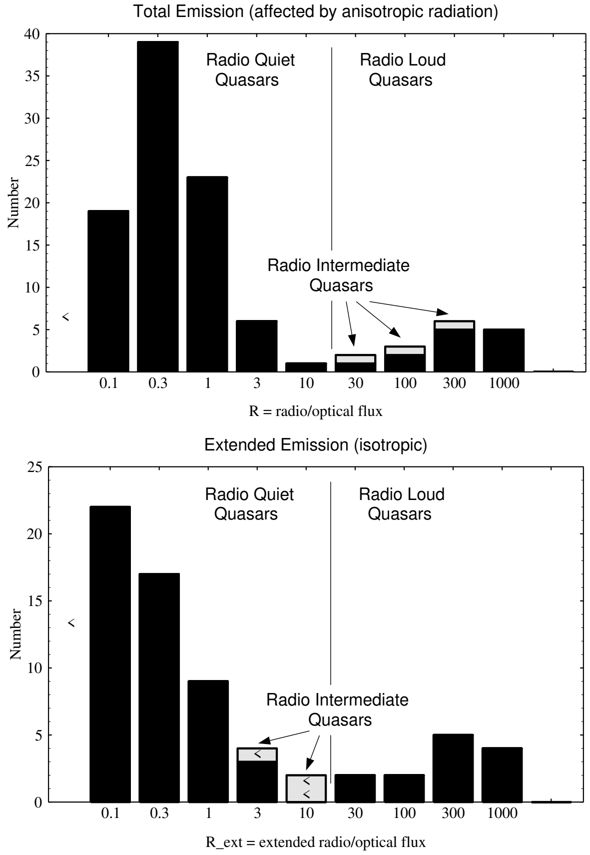

Figure 1: Distribution of the R-parameter (ratio between radio and optical flux) for an optically selected sample of quasars with steep radio spectra (from Falcke et al. 1996a). The RIQ are added with gray shades. While in total flux they rival some of the fainter radio loud quasars with their bright, flat-spectrum radio core, their extended emission is comparable only to radio-quiet quasars.

3.3 Radio-intermediate quasars

Miller et al. (1993) and Falcke et al. (1995 & 1996b) identified a small sample of radio-intermediate quasars (RIQ) which sparsely fill the space in R between radio-loud and radio-quiet quasars. They have optical+UV luminosities between 10^{45} and 10^{47} erg/sec, just like the bulk of the radio-quiet quasars and unlike radio-loud quasars which can be found only above 10^{46} erg/sec in the PG sample. They are typical flat-spectrum, core-dominated quasars, but their R parameter is too low for them to be boosted radio-loud quasars. If they were boosted radio quiet quasars instead, their number and R-distribution would indicate a bulk Lorentz factor of $\gamma_{\rm j}$=2-4. For at least the three low-redshift RIQ, there is no extended emission above a level of a few mJy—far below what is expected for any radio-loud quasar—neither on the VLA A- & D-array (Kellermann et al. 1994) nor on the EVN & MERLIN scales (Falcke et al. 1996a; see also Fig. 1, bottom). At least one source, III Zw 2, has shown outbursts indicating a brightness temperature of 10^{12} K (Teräsranta & Valtaoja 1994) which requires relativistic boosting, while VLBI observations of the three low-z sources indicate at least lower limits of several 10^{10} K. III Zw 2 is the most interesting source in this respect since it is the most variable source with a huge outburst every few years but which has so far resisted attempts to resolve any structure with VLBI (e.g. Kellermann et al. 1998).

In the meantime, since the early papers have been published, one other prediction has been verified. In Falcke et al. (1996a), we suggested that in order to test the idea of the RIQ being intrinsically radio-quiet, at least half of the flat-spectrum RIQ should have spiral host galaxies. So far, powerful radio galaxies and radio-loud quasars have turned out to reside in elliptical hosts, while radio-quiet quasars seem to reside in a mix of spiral and elliptical galaxies (Kukula et al. 1997a). Luckily, two of the three low-redshift RIQ were part of recent host galaxy studies: HST observations of PG 1309+355 (Bahcall et al. 1997) and NIR observations of III Zw 2 (Taylor et al. 1996) have now shown that indeed both galaxies are spirals. This finally confirms that the RIQ cannot be and never will be radio-loud quasars (as they have been classified occasionally in the past)—unless they merge and form an elliptical galaxy perhaps.

In summary, the so far identified and studied RIQ meet all the requirements for intrinsically radio-quiet quasars, whose relativistic jets accidentally point towards us. Moreover, since only a very small fraction of quasars will point towards us, one can infer also that a large number—if not all—of the remaining radio quiet quasars must harbor relativistic jets.

3.4 Direct observations of jets

The only piece missing now is direct confirmation of relativistic jets in radio-quiet quasars; specifically superluminal motion has not yet been observed. This is, however, not surprising given the observational difficulties for these weak sources. VLBI observations of radio-quiet quasars have just recently begun and even they lack the sensitivity to detect additional components besides the core (Blundell, priv. comm.). Deep, long-integration VLBI observations of radio-quiet quasars are certainly needed. For example we are currently performing a study of III Zw 2, where we monitor the source and wait for an outburst which then can be observed directly with the VLBA. The last outburst in December/January 1997/98 seems to be very promising and preparations for the VLBI observations are under way. A second route to follow are deep, high-resolution VLA observations of radio-quiet quasars to look for evidence of the extended radio structures which were seen already in some snapshot maps. First results of such a project seem to indicate that radio quiet quasars indeed harbor Seyfert-like jets (Kukula et al. 1997b)

Fortunately, already now are results available which can, at least in part, answer whether direct evidence for jets in radio-quiet quasars exists at all. First of all VLA observations of Kellermann et al. (1994) have already revealed a number of radio-quiet quasars with weak, bi-polar radio-structure. Secondly, there is a large regime, where the Seyfert galaxies and quasar classifications blend into each other and it may be useful to study Seyferts rather than quasars, which are closer and appear brighter on the sky, and their jets in greater detail. In the next section I will report some results we have obtained using the HST and the VLA for Seyfert galaxies and which might be helpful for the interpretation of quasars as well.

4 Seyferts

Seyfert galaxies were first noted because of their strong emission lines coming from their nucleus, which is emission of hot gas ionized by an AGN. After the advent of the VLA a number of radio surveys have shown that, besides their extended emission line regions, Seyferts also possess – sometimes very faint – radio emission which is very often bi-polar (Ulvestad & Wilson 1984, and previous papers). Seen at higher resolution one finds a strong tendency for the circumnuclear emission-line and radio morphologies to be aligned in Seyfert galaxies (e.g. Unger et al. 1987; Pogge 1988; and Haniff, Wilson & Ward 1988). This strongly suggested that the ejection of the radio plasma and the excitation of the emission line gas were related and that the ionizing radiation escapes preferentially from the active nucleus along the radio axis. Here the Hubble Space Telescope (HST) has made an enormous impact: seen with the superior resolution of this telescope the structure of the emission lines gas was revealed and in some case shown to be well-defined cones (e.g. NGC 1068, Evans et al. 1991; NGC 5728, Wilson et al. 1993; NGC 5643, Simpson et al. 1997), which seemed to confirm an anisotropic escape of ionizing photons from the nucleus. This is most popularly explained by the presence of an optically thick 'obscuring torus' (Antonucci 1993), which is able to collimate the intrinsically isotropic ionizing radiation (see, e.g., Storchi-Bergmann, Mulchaey & Wilson 1993) from the AGN. In addition, a number of galaxies display the 'ionization cone' morphology when an excitation map is made, e.g. in [O III]/(Hα+[N II]).

The close connection between the radio ejecta of Seyfert nuclei and their narrow line regions (NLRs) initially became apparent from their similar spatial extents and from strong correlations between radio luminosities and [O III]λ5007 luminosity and line width (de Bruyn & Wilson 1978; Wilson & Willis 1980; Whittle 1985, 1992). Spectroscopic studies of the NLR (Baldwin, Wilson & Whittle 1987; Whittle et al. 1988), have revealed that the kinematics of the gas are often clearly affected by the radio jets. Such interactions could play a role in determining the structure of the NLR within the region ionized by the nucleus. In a handful of cases, HST has shown a clear spatial correspondence between the radio and emission-line distributions (e.g. NGC 5929, Bower et al. 1994; Mrk 78, Capetti et al. 1994, 1996; Mrk 1066, Bower et al. 1995; Mrk 3, Capetti et al. 1996; ESO 428–G14, Falcke et al. 1996c), indicating that the radio ejecta strongly perturb the ionized gas, at least in these objects. It has also been suggested that the hot gas associated with the shocks generated by the interaction between the radio ejecta and the ambient medium is a significant source of ionizing radiation (e.g. Dopita 1995; Dopita & Sutherland 1995; Bicknell et al. 1997; see also reviews in Morse, Raymond, & Wilson 1996 and Wilson 1996).

It is therefore of great importance to study more Seyfert galaxies at the high spatial resolution which only HST can provide, to determine whether the morphology of the narrow line region is determined by the nuclear ionizing radiation or by the interaction of radio jets with the interstellar medium, or by a combination of both.

In Falcke, Wilson, & Simpson (1998) we presented images taken with the Wide Field and Planetary Camera 2 (WFPC2) of seven Seyfert 2 galaxies (see Fig. 2), selected on the basis of possessing either extended emission-line regions (as seen in

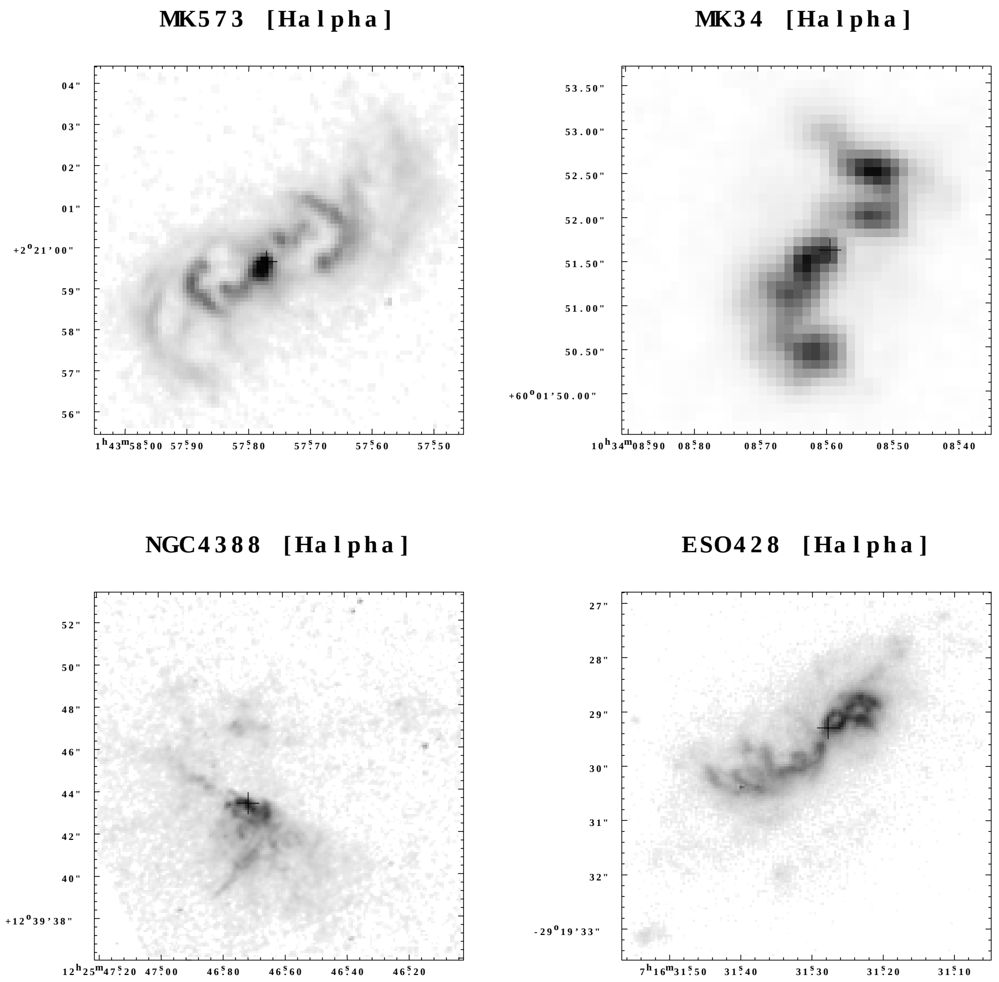

Figure 2: Narrow band HST images of Seyfert 2 galaxies in the Hα emission line from Falcke et al. (1998)

ground-based images) or broad lines in polarized light. For each galaxy images in the light of the [O III] λ5007 line and the Hα+[N II] $\lambda\lambda$6548,6583 blend were taken. In addition we also obtained new radio maps taken with the Very Large Array (VLA), almost all in 'A-configuration', providing an angular resolution comparable with that of the HST images. Taken together, these allowed us to compare directly the structures of the line-emitting gas and radio plasma on scales of tens of parsecs.

And indeed in four of the seven galaxies (Mrk 573, ESO 428−G14, Mrk 34, NGC 4388) we found bi-polar structures in the excitation maps (i.e. the maps obtained by dividing the [O III] by the Hα map, Fig. 3) and a number of finer structures in the emission line regions of all galaxies (with the exception of one, Mrk 1210, which was basically unresolved). In addition, the high quality radio maps of the galaxies we obtained, show the considerable diversity one can find in the radio structure of Seyferts, all of which indicate the presence of a jet outflow: narrow, filamentary jets (ESO 428−G14), triple structures with a core and two hotspots (Mrk 573), jets plus two hotspots (Mrk 34), radio plumes and limb-brightened lobes

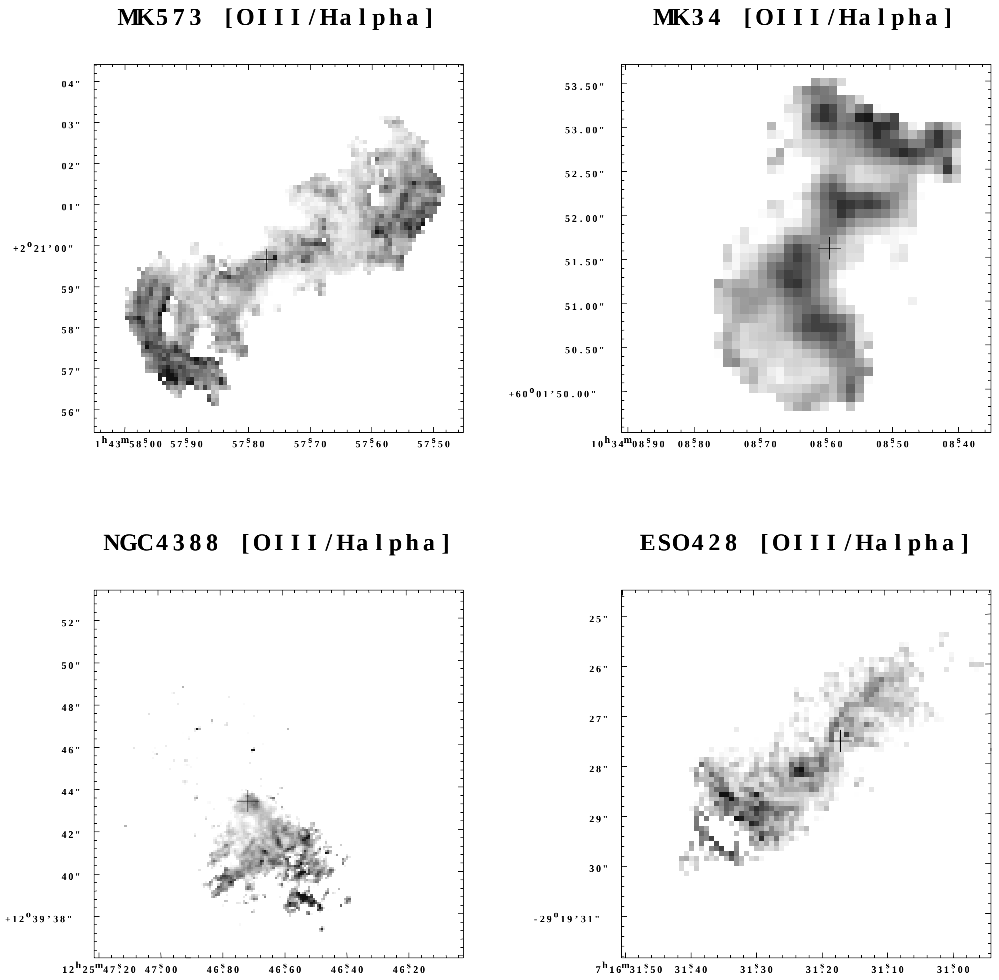

Figure 3: Excitation maps (O III/Hα) for the galaxies in Fig. 1. Dark shades indicate higher excitation. The overall structure of the highly excited gas resembles cones and bi-cones.

(NGC 4388), etc. (Fig. 4).

Even though the dynamic range of Seyfert radio maps is naturally lower than what one can obtain for the much brighter radio galaxies, this diversity is much larger than what we find in the latter. This is of course readily understood, since Seyfert jets are much more subject to jet-ISM interaction than FR II radio galaxies, because of their orders of magnitude lower absolute jet powers. Morphologically, this interaction can be seen in many images of the HST: e.g. in Mrk 573 and Mrk 34 the radio hotspots coincide with regions of reduced excitation, the bow-shock structure in the emission-line gas of Mrk 573 is most certainly caused by the action of an outflow as indicated by the presence of the radio hotspots, and the filamentary emission-line structure in ESO 428–G14 finds its detailed counterpart in the filamentary radio jet.

It is quite obvious from this data that there is not only a close correlation between the radio and the emission-line morphologies, but that *the radio jet-ISM*

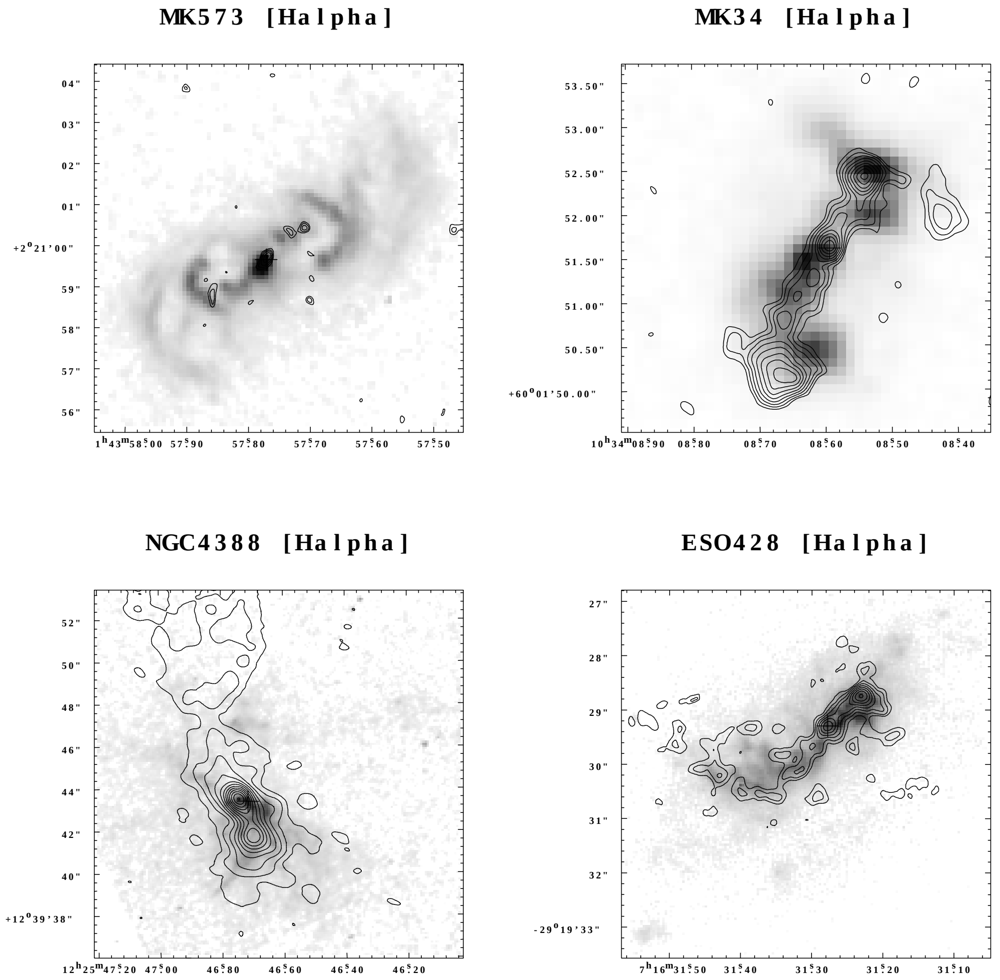

Figure 4: The same images as in Fig. 1 with the VLA radio contours overlaid. The observed wavelengths are 3.5cm for Mrk 34 and NGC 4388 and 2 cm for Mrk 573 and ESO428–G14. The direct relation between radio and optical emission is obvious.

interaction is an important effect which strongly influences the excitation and morphology of the NLR.

Does this mean the unified scheme is wrong? Is the bi-polarity of the NLR and are the ionization cones just illusions of a weary astronomer's soul longing for a simple scheme to explain the Seyfert world? Are all the structures seen in the NLR produced by widening, self-excited matter outflows as Dopita and others suggest?

Fortunately, in at least two cases we can find good arguments, that the anisotropic photon escape scheme remains still valid: In Mrk 573 and NGC 4388 'ionization cones' (Pogge & De Robertis 1995; Capetti et al. 1996; Pogge 1988; Corbin et al. 1988) were already known from ground-based observations on the arcsecond scale and we found an equivalent counterpart on the sub-arcsecond scale with identical opening angle. This continuation and the straightness of the cones clearly favor some kind of obscuring 'torus' with well defined inner edges around the nucleus that leads to a beamed ionizing continuum. Attributing these cones to the action of an outflow seems unreasonable, since the radio ejecta we do see have not only a very different appearance in both galaxies despite similar cone structures, the jets are also themselves subject to collimation by the galaxy, i.e. as seen in the constriction of the northern lobe of NGC 4388, and therefore are nothing like the proposed freely expanding, conical outflows. On the other hand, Mrk 573 has not only a straight 'excitation cone' but, with its bow-shaped emission line strands, is also the clearest example of a jet shaped NLR. Consequently, any successful model of the NLR of this galaxy will require a *composite model that includes photo-ionization from a central source* and *the impact of a radio jet*.

Other examples for the shaping of the NLR by the jet are ESO 428−G14 and NGC 4388. The former exhibits well collimated, irregular emission-line strands on one side and a figure "eight" morphology on the other. The latter has been interpreted as two helical emission-line strands wrapping around a radio jet (Falcke et al. 1996c). The overall structure of the NLR and of the radio jet in ESO 428–G14 is perhaps the most bizarre one can find. In NGC 4388 a bright spike is seen in the ionized gas at the end of the southern jet, while the radio plasma to the north flows apparently unhampered out of the galaxy disk and forms a large ($\sim$ 1 kpc) radio plume. This structure is reminiscent of the radio lobe found, for example, in NGC 3079 (Seaquist et al. 1978) and a few other galaxies (Ford et al. 1986). This kind of limb-brightened radio lobe stands in marked contrast to the well-collimated, stranded jets in ESO 428−G14 and NGC 4258 (e.g. Cecil, Wilson, & Tully 1992). An important difference is that NGC 3079 and NGC 4388 have jets which escape almost perpendicular to the galaxy plane, while in NGC 4258 and perhaps ESO 428–G14 the jet appears to be directed into the disk of the galaxy. The difference in radio morphology may then be ascribed to the much higher external gas density when the jet is in the disk rather than in the galaxy halo.

What remains unclear, however, is the exact nature of the jet/ISM interaction in our Seyferts. To what degree are jet induced shocks responsible for the excitation of the gas? Are there regions, where shock excitation dominates the photo ionization from the nucleus? What amount of energy is locally dissipated in the jets due to this interaction? To answer these questions the observation of only two emission lines is not enough and long-slit spectroscopy will be needed. For ESO 428–G14, the necessary HST time for such observations has been allocated, and other projects will address similar questions in the future. Moreover, some recent results obtained with the FOC on board the HST already now strongly support the jet/ISM interaction picture (Winge et al. 1997, Axon et al. 1997).

At least in a very simple way the jets must have an influence on the excitation of the gas: e.g. the reduced excitation (i.e. [O III]/(Hα+[N II]) ratio) of the inner emission-line arcs in Mrk 573 is consistent with a lower ionization parameter which can be understood if the arcs represent gas which has passed through a radiative bow shock, cooled and increased in density. A similar effect is seen in Mrk 34, in which the radio lobes coincide with a low-excitation region, while the jet itself is surrounded by high-excitation gas. The wiggles seen in the radio jet of this galaxy could possibly be interpreted as some kind of Kelvin-Helmholtz instabilities between the radio plasma and the surrounding, ionized gas. Looking at all the galaxies in our sample, there seems to be indeed a tendency for radio lobes to coincide with lower excitation regions, presumably a result of compression of the ambient gas.

Finally, we can now come back to our initial question about the presence and importance of jets in general. Especially with respect to the situation in radio-quiet quasars, we are now much more prepared to give a positive answer. Some of our galaxies (e.g. Mrk 34 and Mrk 573) have [O III] luminosities comparable to radio-quiet, low-redshift quasars. Hence, for such objects, we are discussing a regime in which the quasar and Seyfert classifications indeed overlap. From their radio flux it is clear that the Seyferts in our sample belong to the radio-quiet class of AGN, yet they not only show jets, but the jets are also kinematically important for the emission-line gas. The jets we find in Mrk 34 and Mrk 573 would in fact resemble some of the double structures seen by Kellermann et al. (1994) in radio-quiet quasars, if placed at a larger distance and observed with lower sensitivity.

5 Compact radio cores

The advantage of the strong interaction in extended Seyfert jets for the qualitative discussion of the importance of jets turns into a major disadvantage if one tries to obtain quantitative statements about jets, since any model naturally would require many parameters. Hence, extended Seyfert jets do not serve well as standard probes for the energetics of jets and one needs a different tool if one wants to compare large samples of sources with each other. Fortunately, jets in AGN are coherent structures with scales from a few AU up to several megaparsecs and one can try to study different parts of the jet in order to get the same answer.

For example, we can use the large, extended lobes of radio jets to estimate their total power, e.g. by calculating their minimum energy content from synchrotron theory or from their interaction with hot, x-ray emitting gas and dividing by the life time of the sources (e.g. derived from spectral aging). The derived powers (which are often *lower* limits) are very high – up to 10^{45-47} erg/sec (Rawlings & Saunders 1991) and the only reasonable place where such enormous amounts of energy can be released is deep in the potential well of a super-massive black hole; this is also indicated by VLBI and variability observations (also gamma-ray observations), which suggest that jets indeed come from a sub-parsec scale. However, ten gravitational radii ($R_{\rm g} = GM_\bullet/c^2$) for an extremely massive black hole of $M_\bullet = 2 \cdot 10^9 M_\odot$ correspond to $3 \cdot 10^{15}$ cm, while the size of hotspots, where the jet terminates, can be several kiloparsecs ($> 3 \cdot 10^{21}$cm; e.g. Leahy et al. 1997) and the lobes are even larger. This yields an expansion factor of 10^6 and more. Hence, if the jets would suffer adiabatic losses due to their lateral expansion (i.e. they would work against the ISM all the way), their total energy losses would scale as $r^{-2/3}$ for a relativistic plasma, and in our case we would have to take losses of 4 orders of magnitude into account. That would require the jets to start with initial powers of 10^{49-51} erg/sec, corresponding to accretion rates of $10^{2-4} M_\odot$/yr and Eddington luminosities for black holes with a mass of $10^{10-12} M_\odot$. From all what we know today, this seems to be too high and one must conclude, that, at least part of the way, the jet does not suffer adiabatic losses and is not in pressure equilibrium with the ISM.

One region were this "inflationary phase" is likely to happen is close to the nucleus, where flat spectrum radio cores are produced and the energy density in powerful jets can be $1 - 100$ erg/cm^3 and above, compared to 10^{-12} erg/cm^3 in the local ISM. Hence, here we will assume that indeed the jets are initially freely expanding after they leave the nozzle and that the energy of the rebounding shocks driven into the jet by the interaction with the ISM is negligible compared to the overall power of the jet. This scenario is in marked contrast to most numerical simulations of jets, where usually a situation close to pressure-equilibrium is assumed. Hence, we suppose that the jet will start to expand into a cone with the opening angle of its Mach cone. A simple calculation shows that the radio spectrum expected from such a configuration will be flat with a constant brightness temperature as a function of size and frequency (Blandford & Königl 1979). The flux of these radio cores is then directly related to the jet power and the inclination angle, if relativistic boosting is important, and environmental effects should be of minor significance. Therefore, the compact radio core, much more than any other part of the jet, allows us to directly probe jet-related properties. Of course, in reality the situation will not be quite as simple, e.g. the radial pressure gradient in the jet will lead to some acceleration of the plasma and will tend to invert the spectrum if the plasma is relativistic (Falcke 1996b) and at some point external collimation and interaction with dense clouds will not be completely negligible anymore.

Nevertheless, compact radio core fluxes have been used successfully to investigate jet powers of large samples. For example in Falcke et al. (1995) we compared the radio core fluxes of a sample of optically selected quasars with model predictions of the flux distribution and found that for radio loud quasars the total jet powers have to be of similar magnitude as their accretion disk luminosities and their power in the extended lobes. The same conclusion was reached by Celotti & Fabian (1993) and by Celotti et al. (1997). Quite interestingly, the latter paper used a large sample of quasars, but, in addition to a simple radio core model, also used Synchrotron-Self-Compton (SSC) theory to derive a jet power from radio flux and x-ray emission. However, even though the basic result showed again the equality between jet power and accretion disk luminosity, the inclusion of the x-ray data seemed to increase the scatter substantially rather than improving the earlier results, which were based on the radio flux alone.

Despite differences in detail all results so far point to a connection between the optical/UV emission and the radio core fluxes, thus strengthening the idea of a jet/disk symbiosis. But, how universal is this principle? How far does it go? Are there luminosities or source types where this principle breaks down? What happens with jets in quasars if the accretion rate becomes lower and lower? Will they die completely, implying that accretion near the Eddington limit is required for the jet formation, or will the jet just become proportionally weaker, implying that jet formation is an integral part of accretion physics? To learn more about this question one first has to search for and then study jets in low-luminosity AGN.

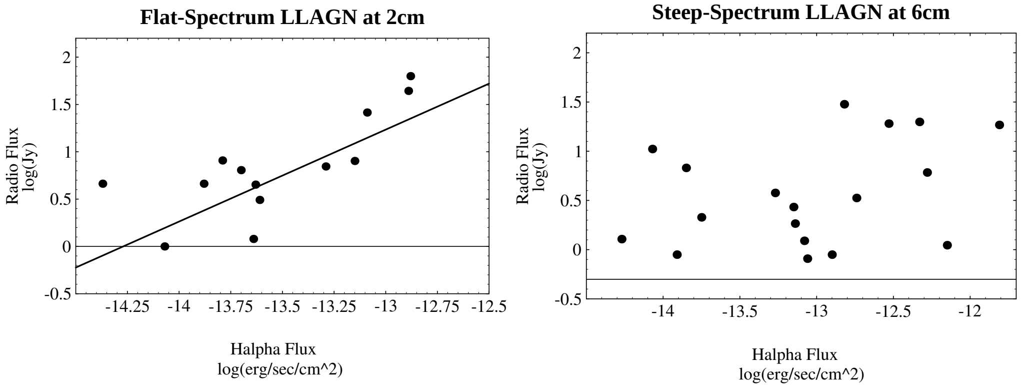

Figure 5: Plots of radio fluxes versus nuclear Hα fluxes for a sample of nearby LINER galaxies. Left: 2cm emission of LINERS in the sample with a compact, flat spectrum emission; Right: 6cm emission of LINERS in the sample with steep spectrum emission.

6 Compact radio cores in LINER galaxies

Ho et al. (1995 & 1997) found that roughly one half of nearby galaxies show signs of nuclear activity in the form of LINER or Seyfert spectra. The bolometric luminosities of these AGN (excluding the host galaxy of course) are in the range $10^{41} - 10^{44}$ erg/sec. Heckman (1980) has speculated that LINER galaxies may preferentially host compact radio cores in their nuclei; according to Falcke (1996b&c) these cores can be interpreted as scaled down versions of the compact radio cores and jets in radio-loud quasars.

To test this, we have performed a VLA A-array survey at 2cm of 48 nearby LINER galaxies (Falcke, Wilson, & Ho, in prep.) from the Ho et al. (1995) sample, to search for compact, flat-spectrum radio nuclei. The 5σ detection limit of the survey was 1 mJy. In total we detected 21 galaxies at this wavelength. Twelve of them have flat and nine have steep spectra. The spectral indices were derived from a comparison with C and X-band observations of the same sample by Van Dyk & Ho (1998) and from additional literature data. We note that out of the 12 flat-spectrum sources, 10 are in spiral galaxies.

Our detection rate of flat-spectrum, compact nuclei at 2cm is relatively high—especially in the spiral galaxies—and confirms the initial hunch that LINERs would make a good sample to detect compact radio nuclei. For comparison, Vila et al. (1990) looked at a sample of Sbc galaxies with nuclear radio components and only detected 2 flat-spectrum nuclei in a sample of 27 galaxies—both were LINERs. In elliptical galaxies, however, the detection rate of compact nuclei is higher (Wrobel & Heeschen 1991).

The mean spectral index we find for our flat spectrum sources is $\alpha = +0.15$ which, however, is rather meaningless since it is based on non-simultaneous data. Comparison with earlier observations shows that some of our sources have varied in flux by up to a factor of five.

Of course, the mere fact that we find these radio nuclei in LINERs does not prove yet that these radio cores are indeed related to the active nucleus or that

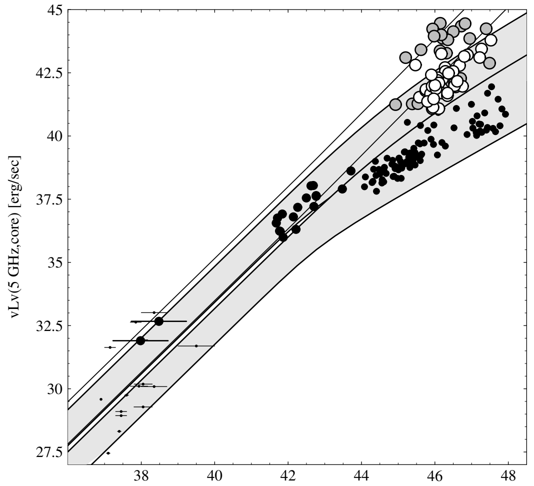

Figure 6: Correlation between accretion disk luminosity (i.e. nuclear optical+UV luminosity for AGN) and monochromatic radio core luminosity at 5 GHz. The shaded bands are the theoretical predictions as presented in Falcke & Biermann (1996) for radio core luminosities as a function of accretion disk luminosity for relativistic jets with randomly oriented inclination angles. The radio cores of the newly added LINER galaxies are given by big dots, quasars are given by open (steep-spectrum, radio-loud) and filled (flat-spectrum, radio-loud) circles, as well as smaller dots above $L_{\rm disk}=10^{44}$ erg/sec (radio-quiet). Sources in the lower left are Sgr A*, M31* and stellar mass black holes (see Falcke & Biermann 1996 for more details).

they are jets. We therefore looked at the relation between radio and optical Hα flux in our galaxies and found a reasonably good correlation for all galaxies with a flat spectrum (Fig. 5, left panel). This is in line with earlier claims of a connection between optical and radio activity (Ekers & Ekers 1973, O'Connell & Dressel 1978). The significance of this possible correlation is greatly strengthened if one plots the same diagram for the LINER galaxies with steep spectrum emission (Fig. 5, right panel) where there is not even a hint of a correlation.

Therefore, we conclude that the radio cores in LINERs are indeed part of the central engine. Moreover, we can compare the radio and emission-line luminosities with the jet/disk model by Falcke & Biermann (1996), to learn more about their nature. The model predicted a specific radio/nuclear luminosity correlation for low-power AGN and is based on the assumption that accretion disk luminosity and jet power in AGN are coupled by a universal constant of order unity. We note that this may remain true even for advection dominated disks, as have been discussed for LINERs (Lasota et al. 1996), if the radiative efficiency of the radio and the optical emission in a jet/disk system are reduced in the same way (i.e. the jet power is proportional to the energy dissipated in the disk rather than to the accretion rate).

For a randomly selected (and randomly oriented) sample, the width ('scatter') of the radio-to-nuclear UV distribution is given by the typical Lorentz factor of the jets. In Fig. 6 we reproduce (without changing any parameters) the figure from

Falcke & Biermann (1996), where the model predictions for low-power AGN was given as shaded bands. We then converted the *narrow* Hα line-luminosities of the LINERs with detected flat-spectrum nuclei to optical+UV luminosities, using the same proportionality factors as for the quasars[1], and we inserted them into the correlation (big dots). Obviously, the LINERs fall exactly into the range predicted for low-luminosity, *radio-loud* jets. This confirms a preliminary version of this diagram which was presented in Falcke (1996c), but was based only on a few ill-selected, famous LINER galaxies.

The result not only strongly suggests that LINERs do have powerful nuclear radio jets—for some individual cases this was known already (e.g. M87; NGC4258, Herrnstein et al. 1997; M81, Bietenholz et al. 1996, etc.)—but is also consistent with mildly relativistic Lorentz factors around $\gamma_{\rm j} \simeq 2$ as used in the model. That should be compared with Lorentz factors of $\gamma \simeq 6 - 10$ derived with the same method for radio-loud quasars (Falcke et al. 1995). For the lower Lorentz factor in LINERs (and also in the Galactic superluminal sources) one can give a very simple explanation, since this terminal velocity is naturally obtained by a relativistic plasma in a simple pressure driven jet (Falcke 1996b). To explain the velocities in radio-loud and radio-quiet quasars, however, one needs an extra mechanism that provides the additional push necessary to go beyond $\gamma_{\rm j} = 3$.

7 Stellar Mass Black Holes

In the sequence of this paper we have slowly moved towards lower and lower luminosities, hence we cannot conclude this paper without a brief discussion of stellar mass black holes, which in terms of absolute luminosity are at the bottom of this distribution of black hole, jet, & disk systems. After all, the discovery of the microquasars has almost led to a revolution in the study of jets. Mirabel et al. (1992) discovered that an X-ray binary, 1E1740.7–2942, near the Galactic Center had symmetric radio lobes not very different from FR I radio galaxies – the major difference only being that this jet was many orders of magnitude smaller and less powerful than those found in AGN. Later, Mirabel & Rodriguez (1994) also discovered a compact radio jet in GRS 1915+105 with apparent superluminal motions, clearly showing that also in the jets of stellar mass black holes relativistic speeds are obtained. The existence of relativistic jets associated with stellar mass black holes was already predicted by Hjellming & Johnston (1988) and Falcke (1994) from the analogy to extragalactic systems. The big advantage of these "small" systems compared to AGN is that their time scale is accordingly shorter. The study of the variability of GRS 1915+105 in x-rays and radio has led to a number of very interesting results, especially concerning the connection between the accretion process and the formation of a jet. For example, in a recent paper Mirabel et al. (1998) found an intriguing correlation between radio outbursts and x-ray flares: it seemed that whenever there was a radio outburst, there was a sudden drop in x-ray emission. Because the x-ray emission is probably coming from the inner parts of an

[1]See Falcke et al. (1995) & Falcke (1996a). The exact conversion factors for LINERs require of course a more thorough discussion. For a few examples (e.g. M81, NGC 4252) this method at least seems to give a reasonable estimate for the nuclear luminosity

accretion disk, Mirabel et al. have suggested that the emission of radio blobs is caused by ejection of material from the inner edge of the accretion disk leading to its temporary disappearance. In Falcke & Biermann (1995) we had already argued for energetical reasons that a large fraction of the energy produced in the inner disk is not radiated away but “dissipated” into the jet. If indeed correct—and further studies will eventually give a much clearer picture of these "laboratory jet systems", this would finally confirm the jet/disk symbiosis picture and will even allow us to uncover some of the details of the coupling between jet and disk.

Another argument for the validity of the jet/disk-symbiosis model comes from the direct comparison of the observed jet parameters and the model predictions, since the basic jet (and disk) parameters for GRS 1915+105 are probably more accurately determined than for any other source and are extremely constraining. Like in the previous section we will again concentrate on the radio cores, where the jet/disk symbiosis model predicts sizes and fluxes of the core as a function of frequency and accretion disk luminosity. The most recent version was published in Falcke (1996b) applied to the radio nucleus M81* in the LINER galaxy M81. The critical difference between the Falcke (1996b) model and the earlier version is just that the velocity field of the jet is calculated self-consistently, taking the acceleration of the jet plasma due to the pressure gradient along the jet (and accordingly the adiabatic cooling) into account and thus reducing the number of free parameters. The model simply assumes that gas is ‘boiled’ somehow to its maximal temperature, thus producing a fully relativistic plasma which leaves a nozzle at ~ 10 (the exact value is not critical) gravitational radii ($R_{\rm g}=GM_{\bullet}/c^2$) and then freely expands into the vacuum, yielding velocities given by Eq. 2 of Falcke (1996b). The ‘radio loud’ model also assumes a ‘maximal’ equipartition jet which is the most efficient radio emitter and generally fixes the main parameters (i.e. $\mu_{\rm p/e}$, $x_{\rm e}$, $q_{\rm j/l}$, see below and Falcke 1996b for details).

We can now use the pressure-driven jet model for M81* without any further modifications and Eqs. 9 and 10-12 of Falcke (1996b) can be directly applied to GRS 1915+105 without any fiddling of parameters. Here we have re-derived the equations for a distance of 12.5 kpc, and an inclination angle of $i=70^{\circ}$ and $i=110^{\circ}$ (for jet and counter jet) as derived for GRS 1915+105 by Mirabel & Rodriguez (1994). Moreover, for simplicity we only give the exponents rounded to one significant digit after the decimal, which allows one to evaluate the sums easily. Finally, we have fixed the intrinsic parameters of the model—which should be of order unity for a radio loud (maximal) jet, as mentioned above—at the canonical values used in Falcke (1996b) and Falcke & Biermann (1995), i.e. $\mu_{\rm p/e}=1.5$, $x_{\rm e}=0.5$, and $q_{j/l}=0.5$. The first two parameters define that the typical Lorentz factor of the radiating electrons are of the order 10^2-10^3 (here $\gamma_{\rm e}=450$), and the last parameter states that the amount of energy radiated by the accretion disk is equal to the total energy input into the jet. The equality of jet and disk power as well as the constancy of these intrinsic parameters is one of the basic principles of the jet/disk-symbiosis, allowing to scale the model over many orders magnitude and still making very specific predictions. The model in this simplified version then predicts the radio emission of the core to be

$$S_\nu = 20\,\mathrm{mJy} \cdot \left(\frac{L_{disk}}{10^{39}\,erg/sec}\right)^{1.4} \left(\frac{M_\bullet}{33M_\odot}\right)^{0.2} \left(\frac{\nu}{8.5\,\mathrm{GHz}}\right)^{0.2}, \qquad (1)$$

for an accretion disk luminosity $L_{\rm disk}$ (here equal to the jet power!), a black hole mass $M_\bullet$, and the observing frequency ν. The expected size of the core (taking jet and counter jet into account) is[2]

$$z(\nu) = 6\,\mathrm{mas} \cdot \left(\frac{L_{disk}}{10^{39}\,erg/sec}\right)^{0.4} \left(\frac{M_\bullet}{33M_\odot}\right)^{0.1} \left(\frac{\nu}{8.5\,\mathrm{GHz}}\right)^{-0.9}. \qquad (2)$$

The parameters $L_{\rm disk}$ and $M_\bullet$ are scaled to the appropriate values for GRS 1915+105 currently discussed in the literature (e.g. Mirabel et al. 1997; Morgan et al. 1997). Of course, this stationary model is only suitable for the quiescent but not the outburst phase. The predicted values fit very well the VLBA observations by Mirabel et al. (1998), where they give a quiescence source size of $\sim$ 6 mas (major axis) and fluxes in the range 20-100 mJy. Moreover, the expected scaling of the core size ($\propto \nu^{-0.9}$) is very close to the observed one ($\propto \nu^{-1}$) and the model also predicts a flat average spectral index for the core of $\alpha = +0.2$. The velocity of the jet in the model grows asymptotically as determined by Eq. 2 in Falcke (1996b), yielding β =0.92 at $10^4 R_{\rm g}$ and $\beta = 0.96$ at the scale of a few mas ($10^8 R_{\rm g}$), where the radio emission is coming from, in good agreement with the observed values. Clearly, the pressure gradient effect must be at work at least to some degree here, since Mirabel & Rodriguez (1994) found that indeed the blobs expand with $0.2c$ at larger scales, thus finding direct evidence that the bulk of the plasma can indeed be described as an expanding relativistic gas. From the calculated values above one can also see that the pressure gradient alone is already sufficient to explain the jet velocities inferred from the observations. Consequently, in GRS 1915+105 there is no need for any additional bulk acceleration mechanisms, e.g. as in centrifugally driven MHD jet models. Finally, one can turn our energy argument around: since we have used the most efficient type of radio jet and assumed that $L_{\rm disk} = Q_{\rm jet}$ (the total jet power), we can say that under any circumstances $Q_{\rm jet} \gtrsim 10^{39}$ is a good lower limit for the total jet power in GRS 1915+105—irrespective of ones belief in the jet/disk coupling.

To conclude this section, it should be noted that the simple idea of a jet/disk coupling, parameterized in a very simple form is able to describe objects from quasars to microquasars, which are separated in luminosity by eight orders of magnitude, to such a detail and accuracy. The same model can describe the radio core in M81 as well as in GRS 1915+105 equally well, by just changing the accretion rate and the inclination angle. We have argued for the existence of this scaling for a number of years now and with more and more data the statement becomes stronger and stronger, so that one can be confident that there is something fundamental behind it.

[2]Please note that the similar Eq. 6 in Falcke & Biermann (1996) has the wrong sign in both exponents, the scaling there has to go as $z \propto \nu^{-1} L^{-2/3}$ – the rest of the paper is not affected by this typo.

8 Conclusions

Today we can make at least one firm statement, namely that there is no known class of active sources, where one suspects an accreting black hole as the central engine, where jets cannot be found in at least a few members of this class. Consequently *jet formation must be in principle possible under almost all circumstances*, whether there are huge or small luminosities, huge or small Eddington-luminosities, or huge or small sizes, there always seems to be a way to make it possible. Given the many observed stellar (Herbig-Haro) jets, this may even be true if the central object is not a black hole.

The question remains, however, whether jets always form in each and every case, i.e. whether each accreting black hole always produces a jet? Even though I suspect the answer to be a strong "yes", with only a feeble "but", a conclusive answer cannot be given yet, since in many cases our sensitivity is not good enough to securely prove or exclude the existence of jets. Much of the progress in the detection of astrophysical jets in recent years has made use of the superior resolution and sensitivity of the VLA, often pushing its ability to the limits, so that further substantial progress may require a further step in radio technology. For Seyferts, the combination of high resolution radio maps with observations of the narrow emission line regions presented in a number of papers, including this one, has now confirmed earlier claims that outflows are a crucial ingredient to the study of Seyferts and therefore most likely also to AGN physics in general. Still, there is a whole universe in front of us that wants to be explored, as for example the low-luminosity AGN in our neighborhood which are receiving more and more attention in recent years. One result is already clear: jets are here to stay, and their importance should not be underestimated as perhaps done in the past by many astronomers not concerned with radio astronomy.

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