The power of jets: New clues from radio circular polarization and X-rays

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Abstract. Jets are ubiquitous in accreting black holes. Often ignored, they may be a major contributor to the emitted spectral energy distribution for sub-Eddington black holes. For example, recent observations of radio-to-X-ray correlations and broad band spectra of X-ray binaries in the low/hard state can be explained by a significant synchrotron contribution from jets also to their IR-to-X-ray spectrum as proposed by 14). This model can also explain state-transitions from low/hard to high/soft states. Relativistic beaming of the jet X-ray emission could lead to the appearance of seemingly Super-Eddington X-rays sources in other galaxies. We show that a simple population synthesis model of X-ray binaries with relativistic beaming can well explain the currently found distribution of off-nucleus X-ray point sources in nearby galaxies. Specifically we suggest that the so-called ultra-luminous X-ray sources (ULXs, also IXOs) could well be relativistically beamed microblazars. The same model that can be used to explain X-ray binaries also fits Low-Luminosity AGN (LLAGN) and especially Sgr A* in the Galactic Center. The recent detection of significant circular polarization in AGN radio cores, ranging from bright quasars down to low-luminosity AGN like M81*, Sgr A* and even X-ray binaries, now places additional new constraints on the matter contents of such jets. The emerging picture are powerful jets with a mix of hot and cold matter, a net magnetic flux, and a stable magnetic north pole.

1 Introduction

Quasars are probably the most important lighthouses of the universe, because they are extremely luminous, compact, and emit at all observable wavelengths. Most of the radio and high energy emission in quasars can be attributed to relativistic jets produced in the vicinity of the central black hole. In blazars also infrared, optical and X-ray emission is produced by these jets. Despite their prominence at all these energies, some basic properties of jets have not been clarified despite intense observing campaigns over the last three decades. Some of these questions are: Why and how are jets produced? What matter are they made of? How much energy is carried in the jet? Why are some jets more radio-loud than others? What is the exact magnetic field configuration?

A possible explanation for the slow progress in answering some of these questions could be that, in contrast to many other astrophysical phenomena, jets were first discovered at rather large distances, i.e. in distant quasars and only in a few cases closer to home. The reason for this is most likely that the radio luminosity of jets scales non-linearly with jet power and is in fact relatively weaker in low-luminosity jets than in quasars (see for example 6). Only in recent years have we become to appreciate that relativistic jets exist over a wide range of distances and over a wide range of black hole masses and accretion rates. This now opens up the possibility to study the physics of jets in a much larger parameter range and to revisit some of the early questions in this context. Here we will concentrate on two relatively new ways of approaching jet physics, namely through their X-ray emission and their circular polarization.

2 X-rays from Microquasar Jets

One important finding of recent years was that X-ray binaries (XRBs) possess relativistic jets as well (17), leading to the term "microquasar". So far these jets have mainly been seen in radio emission, but we will argue here that emission in other wavebands, specifically NIR and X-rays, is almost unavoidable.

A characteristic feature of jets, also in X-ray binaries, is their flat-spectrum radio core which is best seen during phases of relative quiescence (e.g. as in GRS 1915+105, (5)). 10) found that the low/hard-state of the X-ray spectrum is correlated with the presence of a persistent flat-spectrum radio core. He also argued that this flat spectrum of the synchrotron emitting radio core extends up into the near-infrared and perhaps optical regime. This is, in fact, not surprising. The standard model for flat radio spectra (1; 11; 7) suggests that the emission arises from self-absorbed sections in a conical jet, where the smallest scales contribute at the highest frequencies (size $\propto \nu^{-1}$). This is schematically shown in Fig. 1. The interesting point here is that the smallest scale in a system will be set by the size of the black hole. Hence stellar mass black holes will be able to produce flat spectra up to a maximum frequency $\nu_{\rm ssa,max}$ that is much higher than the supermassive black holes in quasars – by a factor given by the ratio of the black hole masses which is of order 10^{5-8}. Therefore XRBs should be much more likely to exhibit direct synchrotron emission in NIR, UV and even X-rays than normal AGN.

This is particularly interesting for the hard X-ray power-laws observed in some XRBs. In a jet spectrum, beyond the turnover point of the flat radio spectrum at $\nu > \nu_{\rm ssa,max}$, the synchrotron emission is optically thin. The shape of the spectrum depends on the electron distribution on the smallest scales in the jet. A thermal distribution leads to an exponential cutoff, but a power-law distribution which is typically observed in luminous AGN jets leads to a hard spectrum with spectral indices ranging from $\alpha = -0.5$ to -1 (energy flux density index: $S\nu \propto \nu^{\alpha}$). The maximum frequency of the optically thin spectrum can be

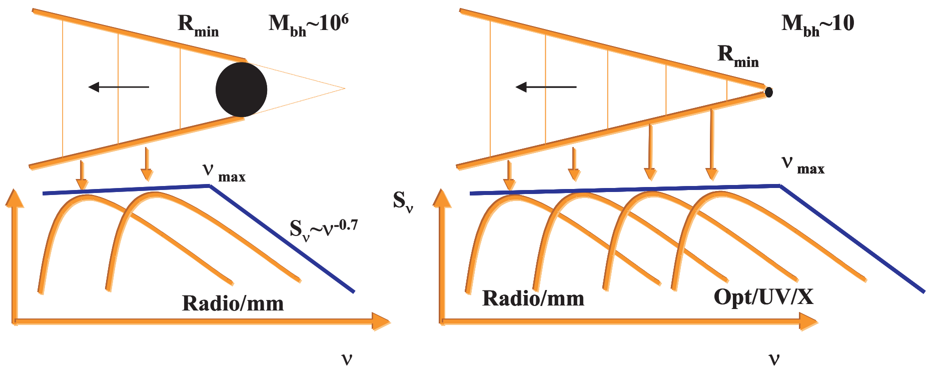

Fig. 1. In a self-similar conical jet model the frequency is inversely proportional to the size. The turn-over frequency of the flat, optically thick part of the jet spectrum is determined by the smallest scale in the system, which should scale with the gravitational radius and the mass of the black hole. Hence, the turnover which in Sgr A* (M$\sim 10^6 M_\odot$) or a quasar occurs somewhere in the submm-range should shift into the optical/X-ray regime for a stellar mass black hole.

found by balancing acceleration and radiation loss times and, as 14) (MFF01) showed, can in principle easily reach several 100 keV fairly independent of the jet power or shock location. MFF01 also showed that such a model can well explain the broad-band spectrum of the X-ray binary XTE J1118+480 (see Fig. 2, top left). Therefore X-ray emission from jets in XRBs is something that has to be dealt with in understanding the spectra of stellar mass black holes.

Of course, the situation may not always be so simple as described in MFF01 for XTE J1118+480, a source which shows almost no sign of reflection components from an accretion disk in the observed spectra (16). Under different circumstances, the disk itself should have a more direct or indirect influence on the X-ray spectrum. One such effect is radiation cooling of highly relativistic electrons in the jet due to photons from the accretion disk. This is important when the accretion rate increases, the disk luminosity increases and, in the truncated disk model, the inner edge of the optically thick disk approaches the inner region of the jet. The drastic increase in photon density near the black hole can then cool most hot electrons and leave the jet very radio quiet as well as suppress the hard X-ray power-law. This situation is shown in Fig. 2, where we start with the published jet spectrum in XTE J1118+480 and move the transition radius arbitrarily closer to the black hole, taking radiation cooling into account. As expected, radio and hard X-rays disappear, while the black-body emission of the accretion disk appears in soft X-rays. There is only some jet contribution to the EUV and soft X-ray spectrum from the jet nozzle left. Therefore, a change in transition radius of the accretion disk could at least qualitatively explain the transition from low-hard to high-soft state and explain why radio and hard X-rays seemingly disappear while the accretion rate goes up.

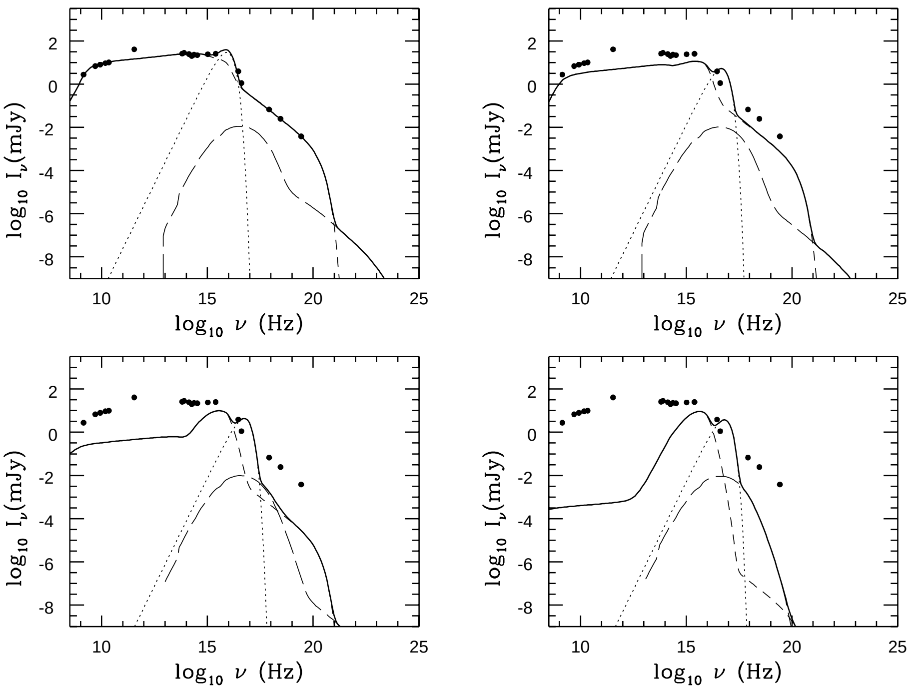

Fig. 2. The self-similar jet model for XRBs: The top left panel is the fit of a jet model to the broad-band data of XTE J1118+480 as shown in 14) together with black body emission from a standard optically thick disk at a large transition radius. The subsequent panels (left to right and top to bottom) show how the spectrum theoretically would evolve from a low/hard-tate to a high/soft-state if one moves the transition radius closer to the black hole. Inverse Compton cooling by disk photons strongly quenches the hard synchrotron emission in the X-rays and suppresses the flat radio spectrum. (From Markoff et al., in prep.)

Such a spectral transition would be difficult to observe in AGN due to the much longer timescales. However, one cannot help to wonder whether such a behavior could also explain the differences between BL Lacs and luminous blazars (or between FR I and FR II radio galaxies/radio-loud quasars as their respective host populations). After all, BL Lacs are intrinsically less luminous than beamed radio-loud quasars but produce much harder and more energetic spectra, extending up to TeV energies with little evidence for disk emission.

3 Microblazars as Lighthouses of the Nearby Universe

The idea that jets in XRBs contribute to the X-ray spectrum[1] has some other interesting consequences. If jet-emission is significant for edge-on sources like XTE J1118+480 it will be even more important when the source points towards the observer. In analogy to AGN, where jets pointing toward the observer are believed to cause the strong blazar emission from radio to gamma-rays, a microquasar pointing towards the observer should appear as a 'microblazar' (18).

This immediately raises the question whether (some of) the ultra-luminous off-nuclear X-ray sources (ULXs), also called Super-Eddington sources or intermediate X-ray objects (IXOs; 4), that have been discussed at this conference (Makishima), are in fact such microblazars. As commonly done in unified schemes for AGN (20) the population of relativistically beamed sources is rather well defined, once one specifies a host population and appropriate parameters for the jets – particularly the bulk Lorentz factor γ_{j}. This allows one to check the validity of such ideas.

Along these lines (13) have investigated a simple population synthesis model for XRBs and compared it with X-ray point source populations in nearby galaxies detected in recent Chandra observations.

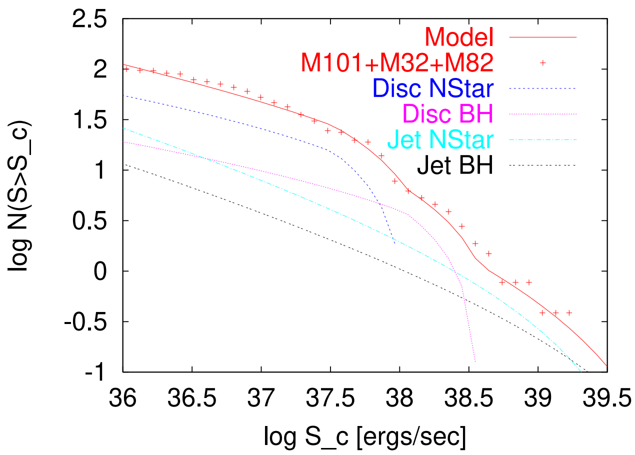

Fig. 3. Log N/Log S distribution of X-ray sources (dots) in three nearby galaxies together with a simple population synthesis model (lines) for isotropic disk and anisotropic, relativistically beamed jet emission for XRBs in low/hard and high/soft states. (From Körding et al. 2001)

The model consists of basically two populations of XRBs, neutron stars and black holes, which emit X-ray emission isotropically from an accretion disk and

[1] In this context it is interesting to note that the possibility of an angle-dependent jet contribution in X-rays was already raised by 19).

anisotropically from a jet due to relativistic beaming. Below a critical accretion rate $\dot{M}_{\rm c}$ (10% of Eddington) the disk luminosity is assumed to scale as $L_{\rm disk} \propto \dot{M}^2$ (according to the ADAF paradigm) and above $\dot{M}_{\rm c}$ as $L_{\rm disk} \propto \dot{M}$. The jet emits with $L_{\rm jet} \propto \dot{M}^{1.4}$ (according to 6) and above $\dot{M}_{\rm c}$ as $L_{\rm jet} \propto \dot{M}$ in the radiation-cooling dominated regime mentioned above. Accretion rates ($\dot{M}$) are assumed to be distributed in a power-law. Figure 3 shows the result of this beaming model together with the data for a $\gamma_{\rm j} = 5$ jet. This shows that the high-luminosity end can indeed be explained by microblazars without violating the low-luminosity end of the distribution or making extreme assumptions about the properties of jets. Hence, as blazars are the most luminous lighthouses of the distant universe, microblazars could be the lighthouses of the local universe.

4 Circular Polarization and the Nature of Jets

So far we have merely used the fact that jets exist and radiate to discuss their observable impact. Their emission and kinetic power depends significantly on their mass content and the electron distribution – specifically the distribution of hot electrons. Recent observations of radio circular polarization in AGN, X-ray binaries, and the Galactic Center black hole (21; 2; 9) suggest that this may only be the tip of the iceberg.

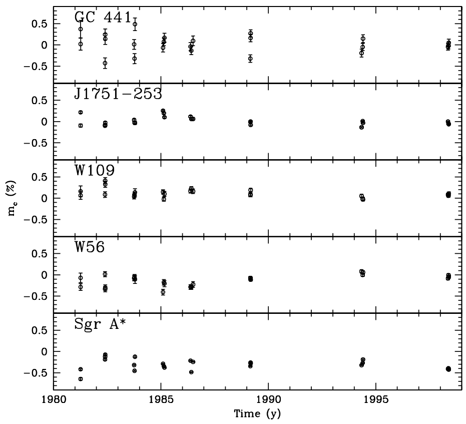

Fig. 4. 20 Years light curve of circular polarization measurements in Sgr A* and nearby calibrator sources with the VLA at 5 GHz. Evidently the level and sign of circular polarization remains constant for Sgr A* over the entire period, while short-term variability may be present. (From Bower et al., in prep.)

One example of such measurements is shown in Fig. 4, where we plot a 20 year light curve of circular polarization in Sgr A* (3) – the radio source coincident with the supermassive black hole at the Galactic Center (15). The source shows about 0.5% circular polarization with a stable sign despite strong flux variations during this time. There is also no detectable linear polarization. The overall spectrum of the source can be understood in terms of a jet model (8).

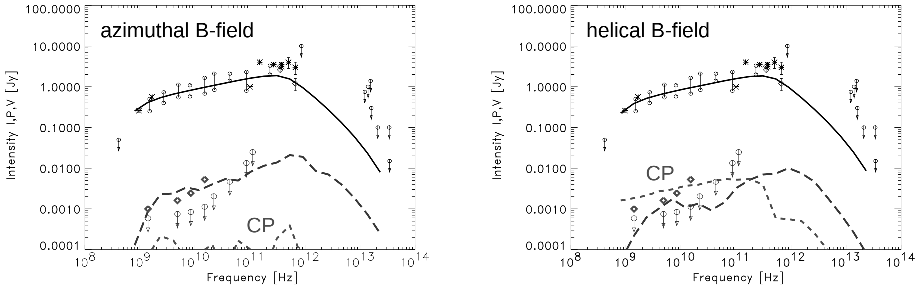

Fig. 5. Data and jet model for polarization in Sgr A*: small circles – average measured total intensity, big circles – measured upper limits for linear polarization, small diamonds – measured circular polarization, solid line – jet model total intensity, long-dashed line – jet model linear polarization, short-dashed line – jet model circular polarization. The left panel is for a turbulent plus a purely azimuthally ordered magnetic field, the right panel is for a turbulent plus a helically ordered magnetic field. A pure azimuthal (plus turbulent) magnetic field is not able to produce significant circular polarization. (From Beckert & Falcke, in prep.)

Circular polarization can be produced through conversion by a bi-refringent medium (such as a magnetized plasma; see 12) where the magnetic field has a component transverse to the line-of-sight and the radio waves are Faraday rotated. De-polarization of linear polarization can be obtained by random Faraday rotation in a turbulent plasma where field components are along the line-of-sight. Both processes are sensitive to the presence of low-energy electrons. The ratio of linear to circular polarization in a jet can be calculated with an appropriate radiation transfer code for various parameters (Beckert & Falcke, in prep.). Fig. 5 shows the result of such a calculation for the case of Sgr A* and two magnetic field configurations: a helical and a purely poloidal magnetic field on top of a turbulent field. Only the former can produce the observed level of circular polarization. Since field-reversals cancel any effect of Faraday rotation and conversion, one needs a field configuration with a dominating component of *one polarity* along the line-of-sight (or along the jet axis for moderately inclined jets).

Such a configuration is most naturally achieved by a helical magnetic field as is presumed to exist in jets. In addition, the number of low-energy electrons producing the conversion and de-polarization needs to be significantly (by 2-3 orders of magnitude) higher than the number of radiating hot electrons. For Sgr A* this increase in particle numbers means that the mass outflow rate and total jet power can be orders of magnitude higher than inferred so far. The stability of circular polarization also indicates that the polarity of the magnetic field (the magnetic north pole) has remained constant over the last two decades. Given the rather short accretion time scale in this source one could speculate that this polarity is related to the accretion of a stable large-scale magnetic field which is accreted and expelled by a jet close to the black hole.

5 Conclusions

Jets are a major source of luminous emission in AGN. Our modeling of jet spectra suggests that this is also the case for X-ray binaries. Jets can contribute to the hard X-rays, and in microblazars X-rays could be beamed to apparent super-Eddington luminosities. The power of these jets could be relatively large, as indicated by the recent detection of circular polarization in various sources which implies a large number of low-energy electrons. The long-term stability of the sign of circular polarization indicates that these jets have a non-vanishing magnetic flux and stable north pole.

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