Mem. S.A.It. Vol. 82, 33

Memorie della

Quasi-stationary and transient patterns in jets

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Abstract. Apparent evolution of relativistic flows as traced by radio emission results from a combination of several factors related to propagation of relativistic blobs or shocks, velocity, density and pressure stratification of the underlying flow, plasma instability and (possibly also) phase and time travel effect. This combination can create an intricate and chaotic patterns of the observed morphological changes in radio emission, which complicates the analysis and interpretation of kinematic and physical properties of the jet plasma. Recent studies have indicated that slow and quasi-stationary patterns in jets are most likely formed by plasma instabilities while faster, superluminally moving patterns are related to highly relativistic plasma condensations produced by the nuclear flares. Some of the stationary patterns may also be related to recollimation shocks or locations where strong non-thermal continuum is produced in jets. Similarities and differences of the AGN and XRB jets in this respect are reviewed.

Key words. galaxies: jets – stars: binaries: general – stars: winds: outflows

1. Introduction

Recent years have witnessed an increasingly wider recognition of the ubiquity of relativistic outflows (jets) in galactic nuclei (Zensus 1997; Falcke 2001) and X-ray binaries (Remillard & McClintock 2006; Mirabel 2010). This has turned jets into an effective probe of the nuclear regions in external galaxies (Lobanov et al. 2006) and the physics of black hole – accretion disk systems in active galactic nuclei (Lobanov 2008, 2010) and X-ray binaries (Mirabel 2010).

In the radio regime, very long baseline interferometry (VLBI) enables direct imaging of spatial scales comparable the gravitational radius, $R_{\rm g} = G\,M_{\rm bh}/c^2$, of the central black hole in AGN using ground VLBI observations at 86 GHz and higher (Krichbaum et al. 2008) and space VLBI observations at centimetre wavelengths (Takahashi 2004). Such high-resolution radio observations also access directly the regions where the jets are formed (Junor 1999)), and trace their evolution and interaction with the nuclear environment (Lobanov 2007, 2008; Middeleberg & Bach 2008).

Jets in both AGN and XRB are formed in the immediate vicinity of the central black hole, in the extreme relativistic environment requiring a full general relativistic magnetohydrodynamic (GRMHD) description for obtaining physically viable models. This overarching closeness of the basic physical settings has prompted a number of investigations connecting together the observed properties of XRB and AGN via their black hole masses, and ra-

Send offprint requests to: A.P. Lobanov dio and X-ray luminosities (the so-called "fundamental plane of accreting black holes; *cf.,* Merloni et al. 2003, Falcke et al. 2004, Körding et al. 2008), as well as via the characteristic timescales of X-ray variability (McHardy et al. 2006; Körding et al. 2007). Different X-ray emission/hardness states observed in the XRB have also been suggested to relate with different states of accretion and jet production (McClintock & Remillard 2003; Fender et al. 2004).

Despite the overwhelming similarities, there is a number of aspects at which XRB and AGN jets are different, and these aspects range from the truly physical (for instance, hotter accretion disks and companion-induced disk truncation in XRB, central neutron star (as opposed to black hole) in low-mass XRB, barycentric motion, and strong precession induced by the secondary star in XRB), to observational (XRB jets are typically detected at a much lower dynamic range than their AGN counterparts), and even to "sociological" ones.

The latter aspects arise sometimes from the AGN and the XRB communities using somewhat divergent "slangs", which may lead to misunderstanding and misconceptions. For instance, the usual comparison of superluminal motions in XRB and AGN relates actually two quite different phenomena: the superluminal features are detected in XRB at about 3–4 orders of magnitude large distances (in terms of the gravitational radii of the central black hole) than their AGN "counterparts", and they, in fact, correspond rather to relativistic motions detected in the hotspots of AGN lobes.

This paper provides a basic overview of the similarities and differences in the observed manifestations of XRB and AGN jets. The discussion is started with a brief review of the current understanding of the physics of AGN jets, which is used as a basis for comparison with the results obtained for XRB jets.

2. Basic physics of relativistic flows

Emission properties, dynamics, and evolution of cosmic relativistic jets are intimately connected to the characteristics of the supermassive black hole, accretion disk and (in the case of AGN jets) broad-line region in the nucleus of the host galaxy (Lobanov 2008). The jet continuum emission is dominated by non-thermal synchrotron and inverse-Compton radiation (Unwin et al. 1997). The synchrotron mechanism plays a more prominent role in the radio domain, and the properties of the emitting material can be assessed using the turnover point in the synchrotron spectrum (Lobanov 1998b; Lobanov & Zensus 1999), synchrotron self-absorption (Lobanov 1998a), and free-free absorption in the ambient plasma (Walker et al. 2000; Kadler et al. 2004).

Jets can be "dissected" (both qualitatively and quantitatively) into five distinct regions, following the physical transitions and evolution undergone by a relativistic flow along the way of its propagation: *1)* launching region; *2)* collimation region; *3)* acceleration region; *4)* kinetic flux-dominated (KFD) flow; and *5)* dissipation (hotspot/lobe) region. Spatial and temporal scales related to these regions are presented in Table 1 for a typical AGN and an XRB object. A brief discussion of each of these regions follows below (cf., Lobanov 2010 for a more detailed description).

2.1. Jet launching

Jets in AGN and XRB should be formed in the immediate vicinity of the central black hole (Camenzind Camenzind (2005)), at distances of 10–$10^2\,R_\mathrm{g}$ (Meier et al. 2001; Meier 2009). The jets carry away a fraction of the angular momentum and energy stored in the accretion flow (Blandford & Payne 1982; Hujeirat et al. 2003) or corona (Merloni & Fabian 2002) and in the rotation of the central black hole (Blandford & Znajek 1977; Koide et al. 2002; Semenov et al. 2004; Komissarov 2005).

The production of highly-relativistic outflows requires a large fraction of the energy to be converted to Poynting flux in the very central region (Sikora et al. 2005). The efficiency of this process may depend on the spin of the central black hole (Meier 1999, 2001). The collimation of such a jet requires either a large scale poloidal magnetic field threading the disk (Spruit et al. 1997)) or a slower and more massive MHD outflow launched at larger disk radii

Table 1. Spatial and temporal scales in AGN and XRB jets

Region	Spatial Scales				Temporal/Frequency Scales			
	Natural Scale [R_g]		Angular Scale		$10^8 M_\odot$ AGN		$10 M_\odot$ XRB	
	l_z	l_r	θ_z	θ_r	τ_z	τ_r	τ_z	τ_r
Launching	10^2	10^1	$0.1\,\mu$as	$0.01\,\mu$as	15 hr	2 hr	200 Hz	2000 Hz
Collimation	10^3	3×10^2	$1\,\mu$as	$0.3\,\mu$as	6 d	2 d	20 Hz	60 Hz
Acceleration	10^6	5×10^4	1 mas	0.05 mas	15 yr	1 yr	1 min	2 sec
KFD Flow (Jet)	10^9	5×10^7	$1''$	$0.05''$	15 kyr	800 yr	15 hr	1 hr
Hotspot	10^{11}	5×10^9	$100''$	$5''$	15 Myr	80 kyr	60 d	3 d
Lobe	10^{11}	3×10^{10}	$100''$	$30''$	15 Myr	500 kyr	60 d	20 d

Notes: Angular scales are calculated for a $10^8 M_\odot$ AGN at a distance of 1 Gpc and for a $10\,M_\odot$ XRB at a distance of 100 pc. The index *z*" indicates length scale along the jet, and the index "*r*" indicates the length scale across the jet (calculated assuming collimation by the magnetic field, MHD acceleration, and adiabatic expansion of the flow. The corresponding temporal/frequency scales pertain to the light crossing times of the respective length scales.

by centrifugal forces (Bogovalov & Tsynganos 2005). The flowing plasma is likely to be dominated by electron-positron pairs (Wardle et al. 1998; Hirotani 2005) although a dynamically significant proton component cannot be completely ruled out at the moment (Celotti & Fabian 1993).

At present, the scales of $\leq 10^2\,R_g$ are barely accessible for direct imaging both in XRB and AGN, with notable exceptions of M 87 ($R_g \approx 2\,\mu as$) and Sgr A* ($R_g \approx 5\,\mu as$). This limits currently observable manifestations of the jet launching region to the domains of time variability and integrated spectrum. Curiously enough, the transverse time scales (light crossing time across the jet) in the launching region are rather similar to those inferred from the high-frequency QPOs in XRB and intraday variability in AGN. In both cases, other explanations (orbital motion in accretion disk in XRB and scintillations in AGN) are often preferred, but the jets may nevertheless play a role in producing this variability.

2.2. Collimation region

Observations of jets in nearby AGN (Junor 1999; Bach et al. 2005) indicate that the flows are collimated on scales of $\sim 10^3\,R_g$, thus indicating a very efficient collimation mechanism. A number of recent works (cf. Meier 2001, Koide et al. 2002, Gracia et al. 2005, Komissarov et al. 2007, Porth & Fendt 2010) have demonstrated the paramount importance of magnetic field for efficient collimation. The resulting collimation is achieved either via self-collimation of the fast, relativistic part of the flow or via collimation of the overdense and slower outer layers of the flow, leaving a very narrow channel for propagation of the underdense relativistic beam.

For the collimation region, the natural time scales (see Table 1 for the respective light crossing times) are close to the typical IDV timescales in AGN and low frequency QPO timescales in XRB, suggesting that the jet plasma on these scales may also contirbute to the respective variability.

2.3. Acceleration region

Acceleration of the flow may be complete within about $10^3\,R_g$ (Meier 2009) or continue all the way to scales of $\sim 10^6\,R_g$ (Vlahakis & Königl 2004), with growing amount of evidence favouring the latter scenario (Bach et al. 2005; Lee et al. 2008).

At distances of $\sim 10^3\,R_g$, the jets become visible in the radio regime (this region is often branded as "core" of the jet). Recent studies indicate that at 10^3–$10^5\,R_g$ ($\leq$ 1 pc, in AGN) the jets are likely to be dominated by pure electromagnetic processes such as Poynting flux (Sikora et al. 2005) or have both MHD (kinetic flux) and electrodynamic components (Meier 2003). At larger scales, the jets are believed to be kinetic flux-dominated, while the transition from Poynting flux-dominated (PFD) to kinetic flux-dominated (KFD) flow remains elusive for the present day observations. One possibility is that the transition occurs still in the region which is optically thick at radio wavelengths. Alternatively, the PFD flow may be sub- or even non-luminous at all. In any case, it would be marginally resolvable with VLBI, and would most likely be associated with the optically thick "cores" in most AGN jets (Lobanov 1998a), again with notable exceptions of the nearest ones, such as M 87 (Junor 1999).

The non-thermal continuum radio emission from the jet core does not appear to have strong shocks, and its evolution and variability can be explained by smooth changes in particle density of the flowing plasma, associated with the nuclear flares in the central engine (Lobanov & Zensus 1999).

This supports the suggestion that jets at these scales are particle-dominated and they reach the equipartition regime downstream, at large distances. (Unwin et al. 1997; Lobanov 1998a; Hirotani 2005). Combining these calculations with estimates of the jet kinetic power provides strong indications that the relativistic fraction of the outflowing material is most likely represented by the electron-positron plasma (Reynolds et al. 1996; Hirotani et al. 2000; Hirotani 2005).

2.4. Kinetic flux-dominated (KFD) flow

The KFD flows, observed in AGN at scales of $\sim 10^6$–$10^9\,R_\mathrm{g}$, provide bulk of the observational material available for relativistic jets. Two distinct regions, with different physical mechanisms dominating the observed properties, can be identified in the KFD flows (cf., Lobanov 2010): 1) parsec-scale flows (~ 10 pc scales) dominated by relativistic shocks and 2) larger-scale jets (≥ 100 pc) where plasma instability gradually becomes dominant.

This picture may be further complicated by transverse stratification of the flow, with the jet velocity, particle density and magnetic field changing substantially from the axis of the jet to its outer layers (cf., Aloy et al. 2001, Gómez et al. 2008). As a consequence of this stratification, shocks and instabilities may in fact coexist on all scales in the jets (Lobanov et al. 1998; Lobanov & Zensus 2001), with instabilities simply remaining undetected in compact flows, owing to limited resolution and dynamic range of VLBI observations.

Parsec-scale outflows are characterised by pronounced curvature of trajectories of superluminal components (Kellermann et al. 2004; Lobanov & Zensus 1999)) and rapid changes of velocity and flux density (Lister et al. 2009). The superluminal components are often found to thread through an underlying pattern consisting of one or several stationary features (Kellermann et al. 2004; Savolainen et al. 2006; Lister et al. 2009).

Specific geometric conditions and extremely small viewing angles could lead to formation of stationary features in relativistic flows (Alberdi et al. 2000). However, a more general and physically plausible explanation is offered by standing shocks (Daly & Marscher 1988; Gómez et al. 1995; Perucho & Martí 2007) or Kelvin-Helmholtz instability patterns propagating at slow, subluminal speed (Hardee 2000, 2007; Lobanov & Zensus 2001).

Stationary features observed near the jet base (at $\sim 10^6\,R_\mathrm{g}$ may indeed represent standing shocks and play a major role in accelerating particles ((Becker et al. 2008; Arshakian et al. 2010; León-Tavares et al. 2010). Such shocks could be responsible for the persistent high levels of polarization in blazars (D'Arcangelo et al. 2007; Marscher et al. 2008). More speculatively, these shocks could also be the sites of continuum emission release due to conversion from Poynting flux-dominated to kinetic flux-dominated flow.

Complex evolution of the moving shocked regions is revealed in observations (Lobanov & Zensus 1999; Gómez et al. 2001; Jorstad et al. 2005) and numerical simulations (Agudo et al. 2001; Mimica et al. 2007, 2009) of parsec-scale outflows. However, the shocks are shown to dissipate rapidly (Lobanov & Zensus 1999), and shock dominated regions are not likely to extend beyond $\sim 100\,\mathrm{pc}$. Starting from these scales, the underlying flow shaped by Kelvin-Helmholtz instability (Hardee 2000, 2007) determine at large the observed structure and dynamics of extragalactic jets (Lobanov et al. 1998; Walker et al. 2001; Lobanov & Zensus 2001; Lobanov et al. 2003; Hardee et al. 2005; Perucho et al. 2006).

2.5. Hotspots and lobes

Jets are expected to gradually lose their collimation and expand into large-scale lobes at distances of $\geq 10^9\,R_\mathrm{g}$. Appearance of the hotspots (still expected to contain a highly-relativistic plasma; Georganopoulos & Kazanas 2004) inside the large-scale lobes suggests that this process can be gradual, affecting first outer layers of the flow and working its way through the jet interior. At the same time, at scales exceeding $\sim 10^{10}\,R_\mathrm{g}$, the helical surface mode of Kelvin-Helmholtz instability is likely to be another factor working on disruption and destruction of the outflows (Lobanov et al. 2003, 2006; Perucho et al. 2007).

It should be noted that most of the proper motion measurements made in XRB refer in fact to the scales of 10^{10}–$10^{12}\,R_\mathrm{g}$, (*cf.*, Mirabel & Rodriguz 1994; Corbel et al. 2002), thus the motions detected in XRBs are more likely to be related to the advance of the lobes and hotspots in AGN (Fomalont et al. 2001). However, the latter have much smaller advance speeds, which raises the question whether this comparison can still be physically valid.

3. Similarities and differences

The above example of comparing spatial scales in XRB and AGN underlines the general issue of relating the jets in these two object classes. The overarching similarity of the general mechanism of matter accretion powering bipolar outflows (outlined overwhelmingly by the unification of the energy output in XRB and AGN made in the fundamental black hole activity plane; Merloni et al. 2003, Falcke et al. 2004, Körding et al. 2008) leads however to quite divergent paths in AGN and XRB outflows. This divergence begins with the XRB accretion disks being hotter and naturally truncated due to a presence of a companion star. It continues then further to the composition of the flow and the environment (with more heavy ions expected in XRB), differences in the extended environment (potentially strong winds from the companion star, and differences between the interstellar and intergalactic environment), and dynamic differences (strong precession and barycentric motion induced by the companion star). All these make the comparisons and relations between XRB and AGN jets rather non-trivial.

One can start this discussion by bringing together the general definitions and jargons used in the two fields, and then considering the main areas in which the comparisons are usually made: the temporary (variability) and spatial (morphology and dynamics) scales in XRB and AGN.

In the XRB "slang", physical states of the outflow are often categorised between "steady, compact jets" with hard (flat) spectrum and "transient, large scale jets" with soft (steep) spectrum. The AGN community uses overwhelmingly the spectral index as the main "divider", thus distinguishing between flat-spectrum emission from ultra-compact jets ("cores") and shocked regions and steeper spectrum emission from the underlying flow, dying shocks and instability-dominated regions. Thus, the steady XRB jets can be in principle physically related to the flat-spectrum parts of AGN flows (especially given that the shock dissipation scales of $\sim 10^8\,R_\mathrm{g}$ are normally unresolved in XRB). The transient XRB jets are then probably more related to the steep-spectrum parts of AGN jets and even lobes.

This picture has however several outstanding issues related to spatial and especially temporal scales inferred for the respective counterparts in AGN and XRB outflows.

3.1. Spatial scales

GRS 1915+105 features proudly a 100 AU-long "compact, steady" jet in low-hard state (Dhawan et al. 2007). This jet is $\approx 10^9\,R_\mathrm{g}$(!!)

long, and no AGN has ever been seen shows a flat spectrum radio emission of such an extent. Thus a simpleminded connection between the "low-hard" XRB and "flat-spectrum" core of AGN (even a "naked" core, without a strong jet) may be problematic.

In the transient, large scale jet observed during the "high-soft" state of XRB, superluminal ejections are traced to separations of $\approx$ 800 mas (GRS 1915+105; Mirabel & Rodriguz 1994) and 30″ (J1550-564, Corbel et al. 2002). These separations correspond to scales of 10^{10}–$10^{12}\,R_{\rm g}$, which well into the scales of radio lobes in AGN. Superluminal components in AGN jets, to which the XRB jets are commonly compared, are typically detected at 10^4–$10^7\,R_{\rm g}$, and therefore the physical conditions in theses superluminal features should be rather different. As was mentioned already, observations of moving ejecta in XRB are most likely related to relativistic motions detected in hotspots of radio lobes in AGN (Fomalont et al. 2001).

3.2. Temporal scales

Flares and component ejections in XRB are often compared to accretion disk instabilities in AGN, while the XRB state transition are commonly related to grand scale accretion episodes in AGN (Celotti 2005; Markoff 2006; Belloni 2006, 2010; Marecki & Swoboda 2010).

With the simpleminded mass-scaling of timescales in XRB and AGN, these comparisons face strong difficulties however. Flares and ejections of new jet components in AGN may be related to characteristic instability timescales in the disk at 20–200 $R_{\rm g}$ (Lobanov & Roland 2005), which then should correspond to periods of $\sim$ 2 sec in a 10 $M_\odot$ XRB. This is much shorter than the typical hour-long timescales of component ejections in XRB – and the latter would have to be scaled up to $\sim$ 1000 years in a $10^8\,M_\odot$ black hole. At the same time, the typical month-long scale of state transition in XRB would correspond to a one million year scale in an AGN, which is seemingly shorter than the timescales of radio active state of AGN as inferred from the sizes of the radio jets and lobes.

Thus, if one adheres to the mass-scaling laws, one is forced to conclude that observations of AGN jets: *a)* probe linear scales that are currently inaccessible for observations in XRB, and *b)* ejections in AGN and ejections in XRB may differ substantially in their physics, with the latter behaving more like major AGN outbursts lasting for decades.

Alternatively, one might suggest that the mass-scaling alone is not sufficient and that environmental differences and energy-loss scales (which are fundamentally similar in AGN and XRB) must be introduced in the comparison as well. The energy losses can be a dominant factor in determining timescales of evolution of flaring emission (Marscher 1983; Marscher & Gear 1985), thus rending practically irrelevant any comparison based on a simple ratio between two emitting regions. Comparisons of variability timescales derived from observations in different bands may be further complicated by energy dependence of the emission losses. For instance, these timescales would differ pretty much the same eight orders of magnitude for synchrotron loss timescale $t_{\rm s} \propto B^2 E^1$, if X-ray variability in XRB is compared to radio variability in AGN (not to forget about the influence of the likely differences in the magnetic field strength in XRB and AGN).

All these examples are only underlying the importance of continuing to analyse carefully the similarities an differences between the observational manifestations in AGN and XRB jets, and attempting to provide a more physically complete basis for such comparisons.

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