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Jet signatures of black holes: From Sgr A* to active galactic nuclei

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Detailed and long-term VLBI (Very Long Baseline Interferometry) studies of the variable jets of supermassive black holes helps us to understand the emission processes of these fascinating phenomena. When observed and traced precisely, jet component kinematics reveals details about the potential motion of the jet base. Following this motion over decades with VLBI monitoring reveals – in some cases – the signatures of precession. While several processes can cause precession, the most likely cause seems to be a supermassive binary black hole in the central region of the AGN. We present examples of the analysis of high-resolution VLBI observations which provides us with insight into the physics of these objects and reveals evidence for the presence of double black hole cores. EHT (Event Horizon Telescope) observations will probably soon tell us more about the jet origin and launching mechanism at the very centers of nearby active galactic nuclei. An important question to be addressed by the EHT and related observations will be whether Sgr A*, the supermassive black hole in the Galactic Center, has a jet as well.

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1 Introduction

Long-term VLBI monitoring of jet component motion in AGN-jets has proved to be a successful tool to unravel the details of physical processes in the very centres of AGN (Active Galactic Nuclei). So far, the immediate vicinity around the presumed active black holes can not directly be imaged with VLBI due to insufficient resolution. While direct imaging would be the preferred tool, tracing jet component motion and determining their kinematics with the help of theoretical modeling yields so far unobservable information from the very centres of AGN – most likely, from close to the presumed active black hole. One of the important paradigms with regard to AGN classification is the unified theme. From radio galaxies to quasars and BL Lac objects the jets are assumed to appear under decreasing angle to the line of sight (Orr & Browne 1982). Based on a detailed analysis of a selected sample of BL Lac objects and quasars we detect so far unknown jet signatures. They bare potential for an improved understanding of the general jet phenomenon, the detection of supermassive binary black holes and the potential detection of gravitational waves.

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2 Jet signatures in parsec-scale jets of active galactic nuclei

2.1 No or slow apparent superluminal motion in (a selected sample of) BL Lac objects – but the jet ridge line itself moves and evolves

It has long been questioned whether BL Lac objects show different apparent motion compared to quasars (e.g., studies of the MOJAVE-survey, CJF-survey). We selected a sample of BL Lac objects (based on peculiar flaring or morphological properties) and studied them in detail based on archival VLBI data (MOJAVE, VLBA archive, etc.). We find that the jet components in 1803+784 (Britzen et al. 2010a), 0716+714 (Britzen et al. 2009), and 1749+701 (see Fig. 1) reveal apparent stationarity of the majority of their jet features. As an example, we here show the results of a re-analysis of MOJAVE VLBA archive data (15 GHz) of the BL Lac object 1749+701 ($z = 0.77$). Figure 1 shows the core separation as function of time (top). For the same time covered we show the evolution of the jet ridge line in the image below. While no or only slow apparent superluminal motion of components can be detected along the jet, the jet ridge line itself shows significant evolution. The position angle of those components closest to the core changes by

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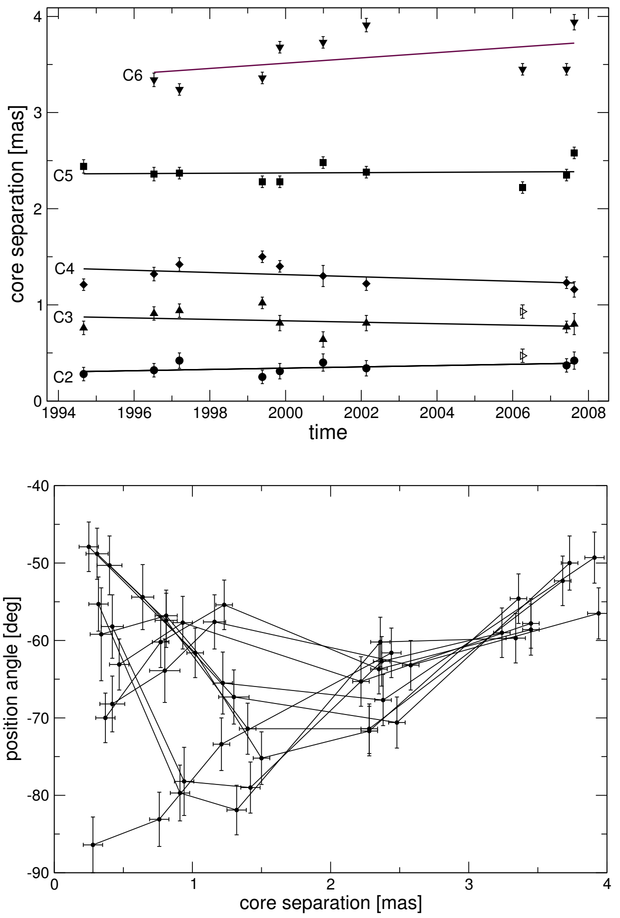

Fig. 1 Jet component motion determined for five jet components (C2-C6) in 1749+701 based on re-modeling of MOJAVE survey data. The *top* figure displays the apparent stationarity of the components. The jet ridge line evolution with time is shown in the image at the *bottom*.

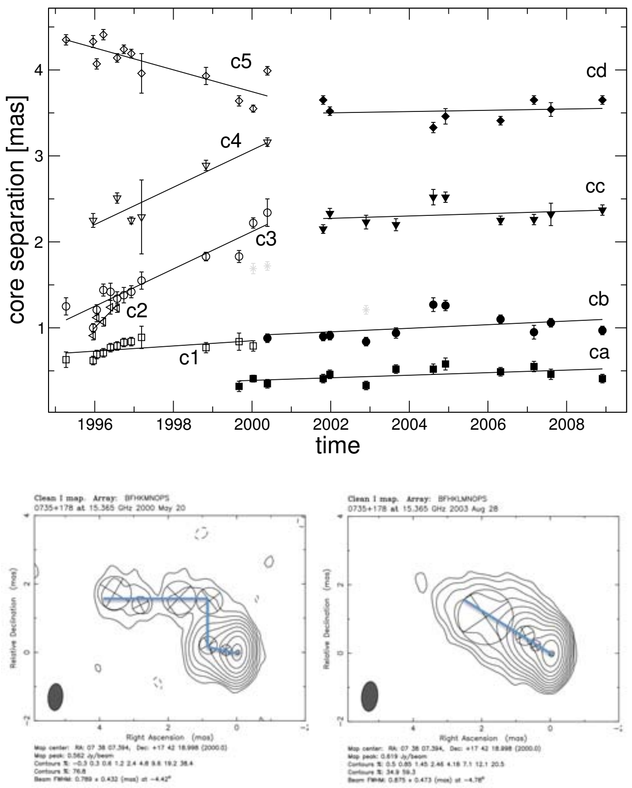

Fig. 2 Mode changes in 0735+178: VLBI jet-morphology and kinematics are correlated and switch between two modes (staircase on the *left* and straight on the *right*). The corresponding jet kinematics is displayed in the *top panel*: The staircase mode reveals apparent superluminal motion and the straight mode apparent stationarity of the jet components.

about 45 degrees in the course of the observations. These two figures reflect exemplary what we find in the investigated sources: The jet ridge line itself moves and evolves in space and time. The jet components – when only investigated in core separation versus time – do not reveal this kind of motion. Thus a detailed analysis of position angle and core separation (or x and y) is necessary to detect this kind of behaviour.

2.2 0735+178: do morphological changes reveal supermassive binary black holes?

Some AGN reveal significantly changing jet-morphologies with time in VLBI observations (e.g., in 3C 454.3, Britzen et al. 2013). As an example, we show pc-scale jet images (Gaussian components superimposed) of 0735+178 in Fig. 2. The jet appears to be significantly curved for several years and then turns into a straight jet. A literature research revealed that the jet of this source significantly changed its shape three times between 1981 and 2002 (Britzen et al. 2010b). Simultaneously with the morphological changes, the kinematic parameters of the AGN jet change. 0735+178 shows apparent superluminal motion (up to about $12\,c$) in the curved state and shows apparent stationarity (~ 0.3–$0.5\,c$) of components in a straight phase. The most simple explanation of the observed correlated (morphological and kinematical) phenomena is the combination of a helical jet and precession. We presumably observe the helical jet under different viewing angles. A smaller viewing angle will amplify the curvature while a larger viewing angle will make the jet appear more straight. The exact cause of the viewing angle changes remain to be explained physically. A likely explanation can be the motion of the jet base due to precession.

Several possible mechanisms for precession have been discussed in the literature. The precession can originate from either the Lense-Thirring effect, or the torque caused by a companion object in a binary system (Katz 1997). While it seems to be possible to cause precession by a misaligned spin/accretion disk system (Caproni et al. 2004), the more likely scenario might involve a binary black hole at the centre of the AGN (e.g., Gong 2008; Britzen et al. 2010b). Since these mode changes represent a new phenomenon with regard to AGN morphology, this offers so far unexplored opportunities with regard to the detection of binary

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systems and the calculation of the parameters of the system. This aspect also bares potential for locating potential merger candidates with regard to the preparations of future gravitational wave detection experiments.

2.3 1308+326: rolling-up of a helix

Many AGN-jets stay in shape – the above presented mode changes seen in 0735+178 so far present an exception from the rule. In another AGN we can follow the evolution of the jet ridge line with time in VLBI observations. We show in Fig. 3 the rolling-up of a helical jet in the quasar 1308+326 ($z = 0.997$, LSP HPQ). This source is part of the catalog (e.g., Piner et al. 2012) of radio reference frame sources of geodetic VLBI (ICRF, Ma et al. 1998; Ma et al. 2009; Jacobs et al. 2014). We investigated and re-modelled the quasar in VLBA archive observations (MOJAVE) to clarify the reason for unusual astrometric position instabilities (e.g., Bouffet, Charlot & Lambert 2012) which could not easily be explained with simple and generally assumed outward motion of jet components.

In Fig. 3 we show a series of nine VLBI images with Gaussian components superimposed. From the earliest image shown (taken in January 1995) to the second last image shown (taken in July 2006) an evolution of the jet is visible. From a rather point-like structure the jet develops and shapes into a more and more clearly visible helical structure. The helical jet shape disappears rather suddenly. The last image shown in Fig. 3 reveals a point-like structure – similar to the first image shown in Fig. 3 (taken in January 1995). This significant jet evolution from a point-like object into a substantially larger and more complex jet structure with helical signature explains the observed shift in the centroid of brightness distribution and as such the astrometric deviations observed within the International Celestial Reference Frame observations (Britzen et al., in prep.). Further data reduction is under way and modeling of a binary black hole system (e.g., Roland et al. 2008; Roland et al. 2013) is in preparation.

2.4 Questioning the standard paradigm for jet component motion in BL Lac Objects

In this (and previous) manuscripts we present evidence, that the jet itself – rather than only the jet components can undergo significant evolution – the jet itself seems to maneuver. Based on the here presented results it seems likely that geometry plays an important role and precession is a crucial part of this. The scenario of jet component motion – at least in the case of the BL Lac objects – seems more complex than generally assumed. Jet component motion – in those sources studied by the authors – is determined by the jet ridge line. Models representing the four dimensional evolution of the jet in space and time might provide realistic parameters of the system. This will be of special importance with regard to the determination of the parameters of supermassive binary black holes.

3 A jet in Sgr A*?

A jet of wind from Sgr A* is expected but evidences for it are rather disputed. The density distribution of relativistic electrons predicted by MHD calculations (e.g., Dexter et al. 2010; Dexter & Fragile 2013; Moscibrodzka & Falcke 2013) predicts a central plane and outflow region. This outflow region is difficult to be measured. For VLBI observations the larger outflow size at lower radio frequencies will be hidden by the the lower angular resolution due to interstellar scattering. VLBI observations at very short millimeter radio wavelengths can overcome the effects of interstellar scattering and allow us to study the source intrinsic structure of Sgr A*. It is possible that the jet is well hidden and rather difficult to detect due to its low surface brightness. Markoff, Bower & Falcke (2007) investigate whether the combined spectral and morphological properties of Sgr A* are consistent with the predictions for inhomogeneous jets. They compare models with VLBA images obtained at 7 mm wavelength. With these experiments the authors show how to hide large-scale outflows and constrain the size of such a jet like feature. Fits with bipolar jet structures describe the data very well. These structures have a high inclination to the line of sight and rapidly fade away toward larger separations from Sgr A*. Based on high resolution VLA radio images Yusef-Zadeh et al. (2012) find evidence for a 3 pc scale outflow from Sgr A* faint continuous linear structure accompanied by a number of weak blobs and centered on Sgr A* with a P.A. $\sim 60°$.

Shahzamanian et al. (2015) investigate the polarization of the optically thin synchrotron radiation in the near-infrared. They find typical polarization degrees of the order of 20 ± 10 % and a preferred polarization angle of $13\pm15°$. This preferred polarization angle is potentially coupled to the intrinsic orientation of the Sgr A* system i.e. a disk or jet/wind that are associated with the supermassive black hole. This points at a rather stable geometry and accretion process for the Sgr A* system. At position angles ranging from 120° to 130° (Eckart et al. 2006a, 2006b) find an elongated NIR feature, an elongated X-ray feature (Morris et al. 2004) and recent discussion by Li, Morris & Baganoff (2013) and a more extended elongated structure called LF, XF, and EF in Fig. 9 of Eckart et al. (2006a). If these features trace a jet, then the preferred NIR polarization angle may be associated with the jet components close to the foot point of the jet. For these components the polarization may be along or perpendicular to the jet direction.

On the other hand it may also be conceivable that the NIR emission is due to hot spots in an accretion disk. In such a scenario the E-vector is mainly perpendicular to the equatorial plane (e.g., Yuan, Xie & Ostriker 2009). A jet or wind may then be driven perpendicular to the intrinsic radio structure of the disk along the position angle of the NIR polarization. At a position angle of about 193° (i.e. $13° + 180°$) we find the mini-cavity that may trace the interaction of such a nuclear outflow (jet or wind). The presence

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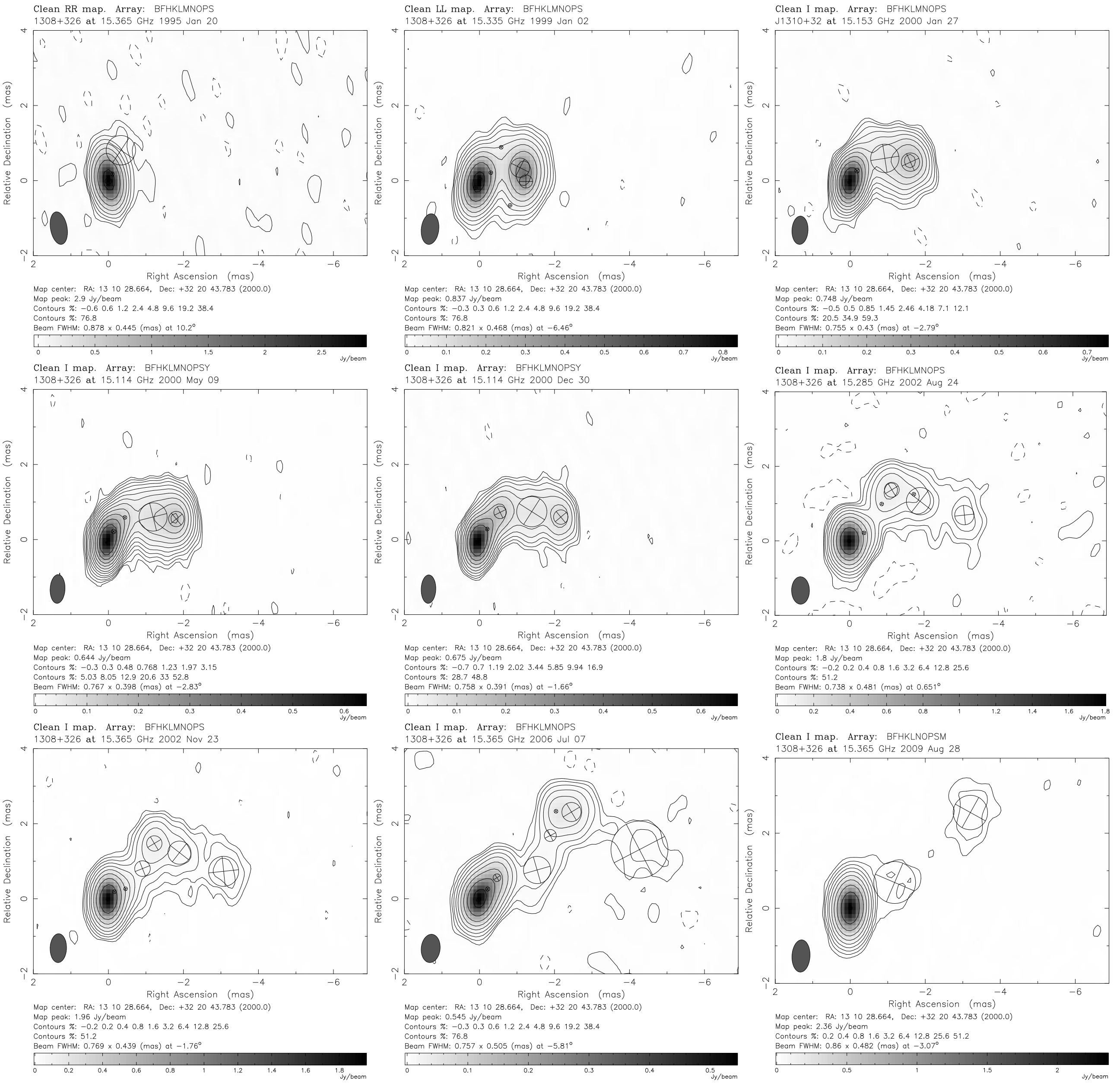

Fig. 3 Series of maps with Gaussian components superimposed of 1308+326 (20.01.1995 – 30.12.2000). VLBA observations at 15 GHz (MOJAVE) and re-modelled by the authors.

of a wind is supported by the cometary tails of sources X3 and X7 reported by Muzic et al. (2010).

Eventually, the EHT (Event Horizon Telescope) will provide high angular resolution and high dynamic range images of the event horizons of the largest supermassive black holes in the sky. These are Sgr A* and M 87 for which one Schwarzschild radius corresponds to an angular size of about 10 μarcsec and 3.7 μarcsec, respectively. These observations may also result in the detection of a predicted putative black-hole shadow (e.g., Huang et al. 2007). This shadow may arise from light trapping by the black hole and its interaction with material in its vicinity.

4 Theoretical aspects of jets

The main properties of jets are that they are highly collimated and that the particles in the jets have very high velocities. The direction of the jets is certainly related to the direction of rotation of the black hole, that is, is most probably correlated to the symmetry of the space-time geometry, that is, of the black hole.

The origin of the high energy of the particles in the jets is not yet clear. Investigations are under way whether the energy of a jet particle may arise from the Penrose process (Lasota et al. 2014) or, more conventionally, by electromagnetic processes.

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The most simple model for a jet is the ballistic model. In this model, the jet consists of charged particles which do not collide and also do not interact. The gravitational field as well as he electromagnetic field of the charged particles will be neglected. This is a dust of charged particles. Within such a model also any viscosity and turbulence is neglected. For such a ballistic model, one can derive analytic solutions (ballistic models have been employed for a first analytic description of the behavior of accretion disks by Tejeda et al. 2012 and Tejeda et al. 2013). This is based on the analytic solutions for the equation of motion of a charged particle in a Kerr-Newman space-time (Hackmann & Xu 2012). The advantage of analytical solutions is that we have a complete description of the phenomena within the model. The disadvantage is, however, that analytically solvable models are certainly not always applicable to real situations.

The Kerr-Newman black hole space-time is given by the metric

$$\mathrm{d}s^2 = \frac{\rho^2}{\Delta}\mathrm{d}r^2 + \rho^2\mathrm{d}\vartheta^2 + \frac{\sin^2\vartheta}{\rho^2}\left[\left(r^2+a^2\right)\mathrm{d}\varphi - a\,\mathrm{d}t\right]^2 - \frac{\Delta}{\rho^2}\left(a\sin^2\vartheta\mathrm{d}\varphi - \mathrm{d}t\right)^2 \quad (1)$$

with the abbreviations

$$\rho^2(r,\vartheta) = r^2 + a^2\cos^2\vartheta, \quad (2)$$

$$\Delta(r) = r^2 - 2Mr + a^2 + Q^2 + P^2\,, \quad (3)$$

where M is the mass of the black hole, a the specific angular momentum (Kerr parameter), and Q and P the electric and magnetic charge of the black hole. If magnetic monopole would exist they could not be distinguished from electric charges on the level of the space-time metric. The corresponding electromagnetic field is

$$A_\mu\mathrm{d}x^\mu = \frac{Qr}{\rho^2}\left(\mathrm{d}t - a\sin^2\vartheta\mathrm{d}\varphi\right) + \frac{P}{\rho^2}\cos\vartheta \times\left[a\mathrm{d}t - \left(r^2+a^2\right)\mathrm{d}\varphi\right]. \quad (4)$$

The equation of motion of a charged particle is given by the Lorentz force equation, that is, the relativistic equation for a charged particle in a Kerr-Newman black hole space-time

$$v^\nu \mathrm{D}_\nu v^\mu = \frac{q}{m}F^\mu{}_\nu v^\nu, \quad (5)$$

where m and q are the mass and charge of the particle, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field of the Kerr-Newman black hole, and D_ν is the covariant derivative given by $\mathrm{D}_\nu B^\mu = \partial_\nu B^\mu + \left\{ {\mu \atop \nu\rho} \right\} B^\rho$, where $\left\{ {\mu \atop \nu\rho} \right\} = \frac{1}{2}g^{\mu\sigma}\left(\partial_\nu g_{\rho\sigma} + \partial_\rho g_{\nu\sigma} - \partial_\sigma g_{\nu\rho}\right)$ is the Christoffel symbol.

In such space-times we have four constants of motion: the normalization constant of the 4-velocity $g_{\mu\nu}v^\mu v^\nu = 1$, the energy E and angular momentum L of the particle as well as the Carter constant C. Insertion of he metric and of the solution for the electromagnetic field in the Lorentz force equation then gives four equations of motion which can be separated and which can be completely analytically solved with Weierstrass elliptic functions (Hackmann & Xu 2012).

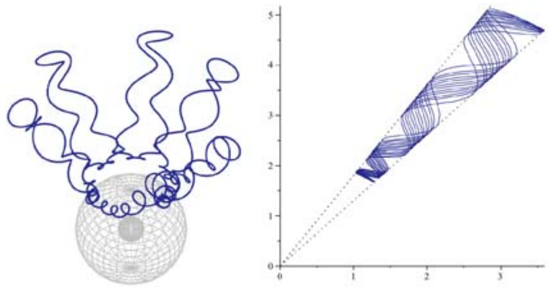

Fig. 4 A jet-like orbit as analytical solution of the equation of motion of a charged particle in the space-time of a charged rotating black hole (Kerr-Newman). *Left*: orbits in three-dimensional configuration space; *right*: the r-ϑ projection, taken from (Hackmann & Xu 2012).

The energy and the angular momentum of the particles describing their trajectory are related to the initial conditions of the particles, and these initial conditions are given by the history of the particles. Most probably the particles initially were in the accretion disks and then approached the black hole. Through the interaction with the black hole (e.g. through the Penrose process) the particles may receive more energy and angular momentum. This process, however, is not yet understood.

Taking the energy of the particle as some given parameter we may calculate orbits of the charged particles. One characteristic set of orbits is given in Fig. 4.

The ballistic model may also serve as first step towards testing alternative theories. As an example, one may take solutions from the Plebański-Demiański class of black hole solutions. For these black hole geometries also analytical solutions of the equation of motion do exist (Hackmann et al. 2009). A further generalization still allowing for analytical solutions of the equations of motion is given by black hole models within a theory of nonlinear electrodynamics of Plebański type. Such solutions are given by Ayón-Beato & García (1998). These solutions describe black holes without a singularity, that is, regular black holes. The solutions of the equations of motion for neutral particles is shown in García (2015), the corresponding solutions for charged particles as stated in the same paper is related to quartic problems and is under development.

In a next step one should take into account the electromagnetic field produced by the moving particles, probably it is possible to start with simplified approximate solutions. We also should take into account turbulence. This very probably can no longer be solved analytically.

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