Evidence for Turbulent Loading of the M87-Jet

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The question how relativistic jets are launched in Active Galactic Nuclei (AGN) is still unsolved. Due to M87's proximity, jet prominence, and the large BH mass, this giant radio galaxy is the best laboratory for investigating the formation, acceleration, and collimation of relativistic jets. This source is one of the two prime objects to be studied in exquisite detail with the upcoming Event Horizon Telscope (EHT) observations. It promises to allow a direct view on the jet launching process itself which so far has not been possible to study observationally. Our investigations show, that the M87-jet visible at 15 GHz already probes a different physical zone compared to the standard blazar-zone we see in AGN jets. We remodeled and re-analyzed 31 VLBA observations at 15 GHz obtained within the MOJAVE programme. The data span a time range between 1995.6 and 2011.4. We performed a detailed investigation of the pc-scale jet kinematics, and the jet ridge line behavior. Special care has been taken to analyze the region close to the 15 GHz core. We find evidence for two different operating modes of the jet of M87: The jet switches between phases where the jet ridge line is (at least) double or the jet axis is displaced vertically and an unperturbed phase where the jet ridge line remains rather straight, only smoothly curved with the jet components aligned along a classical jet axis. The most likely scenario explaining the observed phenomena is a turbulent mass loading into the jet, most probably due to local reconnection processes of a tangled magnetic field, either generated in the accretion disk or the disk corona. In addition, on large scales, a global magnetic structure is required to channel the turbulent flow into what evolves into a large-scale jet. Large-scale jet instabilitites may explain the curved pattern of the observed jet flow.

Keywords: VLBI, M87.

1 Introduction

M87 is the central elliptical galaxy in the Virgo cluster and at a distance of 16.7 Mpc the closest active black hole to our galaxy. The bright jet and counter-jet have been studied intensively in all wavelength regimes (radio to TeV). The M87 jet was the first jet to be observed in the optical regime [6]. Most detailed information for this show-case jet has been obtained in the radio regime with increasing observing frequencies and resolution in recent years (e. g. [1], [13], [8]). The jet is also visible in the optical (HST, e. g. [7]), and in the X-ray regime (e. g. [14]). M87 was the first radio galaxy to be detected in the TeV regime. The temporal coincidence of the TeV and radio flares indicate an origin of the TeV radiation within a few tens of Schwarzschild radii of the radio core [12].

In this manuscript we present an excerpt of our results obtained with regard to the origin of the jet of M87. A detailed description of our analysis and conclusions can be found in [2].

2 Observations and Data analysis

We re-modeled and re-analyzed 31 VLBA observations (15 GHz, MOJAVE) performed between 1995.6 and 2011.4. Gaussian circular components were fitted to the data to obtain the optimum set of parameters within the *difmap*-modelfit programme.

3 A jet operating in two modes

The detailed structure of the M87 jet is shown in Fig. 1 for the epoch (May 2009) of highest quality observations. Our analysis confirms the complexity of the jet-morphology on pc-scales (e. g. [13]). The jet splits into two regimes parallel to an imaginary axis — often described as limb brightening (e. g. [15]). This limb-brightened jet is also confirmed in Global Millimeter-VLBA observations (GMVA) at 43 and 86 GHz (e. g. [9]). The jet of M87 appears to operate in two different modes: In the first mode the jet opens up into a broad jet that consists of two strings (limbs). In the second mode the jet remains straight with only one jet ridge line. In Fig. 2 we examine the jet ridge line behaviour for all epochs. About every two years the jet appears to be in a "straight mode" and is then displaced again. The individual observations deviate in data quality (e. g. number of data points) and time sampling — so we might miss some of the "straight" or "broad" phases. Nevertheless, the detected mode changes seem to be a robust and repetitive effect. There seems to be a transition phase where the jet width is in between the "broad" and "straight" jet phase.

4 Turbulent mass loading

Fig. 3 provides a schematic illustration of our results on the interrelation between the turbulent injection process and the large scale jet appearance. The turbulent mass loading close to the disk surface is a local process, loading different magnetic flux tubes at different time and at different location. The mass loading is physically done by reconnecting magnetic flux tubes originating at the disk surface. On large scales only the global field structure survives, turned into a helical field by the usual magnetocentrifugal driving. The mass loading of the jet, however, is not smooth, but results from the localized reconnection events on the disk surface.

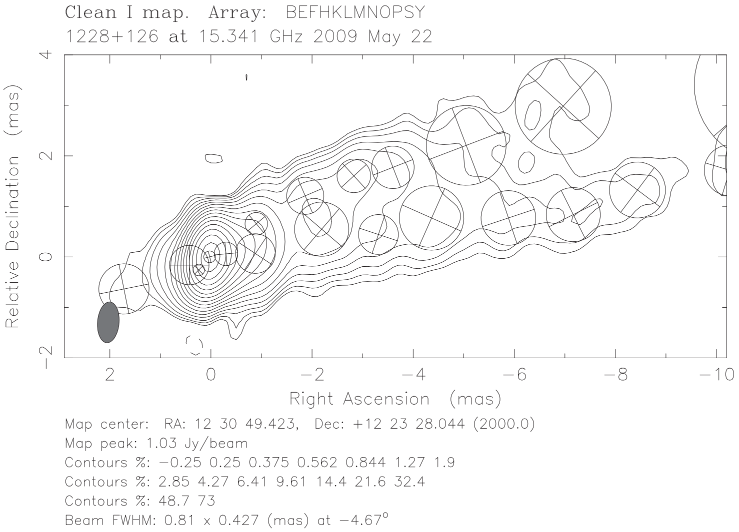

Fig. 1. The typical structure of the pc-scale jet at 15 GHz

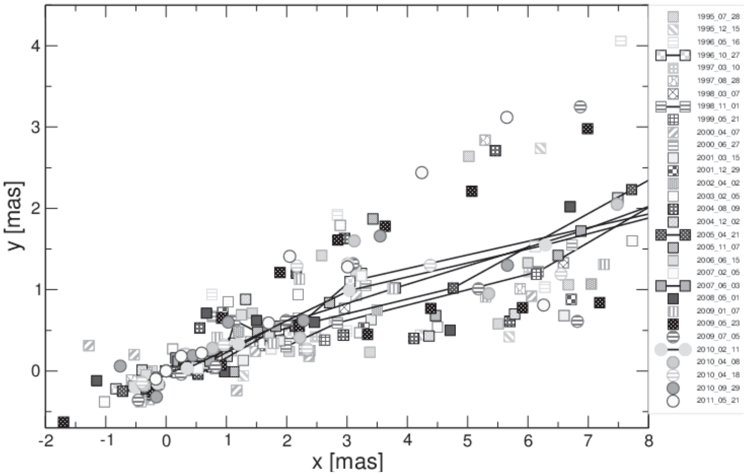

Fig. 2. We show all components found in the model-fitting process in x versus y (inner 8 mas). Phases of a straight linear expansion of the jet are marked by solid lines

Note that in this picture, the mass flux has a predominantely poloidal velocity (as typical for MHD jets), while the magnetic field helix “rotates through” the gas distribution, satisfying the MHD condition. With regard to our results for the M87 jet, turbulent mass loading seems reasonable, considering simulations by [16] who investigated strongly magnetized disk coronae forming from the twisted magnetic flux loops anchored in differentionally rotating parts of the accretion disk, see also [4]. Interestingly, there is a close similarity between our findings and recent ob-

Fig. 3. Schematic illustration of the turbulent mass injection process. Turbulent mass loading close to the disk surface by local reconnecting magnetic flux tubes is skteched. Over long distances only the global helical magnetic field structure survives with a mass loading resulting from localized reconnection events. The figure is kindly provided by A. M. Quetz (MPIA)

servations of solar jets (e. g. [10]) such that also solar jets show evidence for two morphologically different phases of a straight or helical pattern (so-called standard and blowout jets). There are, however, also some significant differences: accretion disks exhibit very strong shearing motions due to Keplerian motion near the black holes [5] which affects the time-scales for the mecahnism of the magnetic reconnection.

We may imagine the disk surface as similar to the solar surface which is magnetically active and shows violent reconnection events, with photospheric convection cells leading to a turbulent surface. The ridge line changes might be caused by kink instabilities. The growth of the kink instability along roating jets with helical fields both for tower jets and propagating jets has been studied in numerical simulations by e. g. [3]. Note that these simulations have been applied for core-collapse GRB jets, however, the main features may also appear in other relativistic jet sources. The 3D formation of jets from disk winds have been simulated by [11]. The result is that jets maintain their long-term stability through a self-limiting process. Putting together the turbulent structure of the inner accretion disk with flaring events of reconnecting magnetic flux tubes in the disk corona, the model of jet knots emitted as *substructure* into a large scale jet magnetic field seems promising. The large-scale, aligned jet magnetic field is visible as jet structure at large distances (kpc — Mpc).

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