Estimating AGN jet parameters from observations of a jet shape break

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1. Abstract

We propose a model of a relativistic jet with the total electric current closing inside an outflow. In such a problem the thermal term plays an important role in the very vicinity of a jet boundary, staying negligible in the major jet volume. The jet boundary shape is obtained in this framework. We show that the jet boundary changes its shape from parabolic to conical as the flow transits from magnetically-dominated to equipartition regime. This interpretation together with the jet shape break observations allow us to estimate intrinsic jet parameters such as rotation rate, total magnetic flux, and the jet power.

2. Current closure and model set up

The relativistic jet structure is governed by Grad–Shafranov and Bernoulli equations. The solution exists if we set the 5 integrals, conserved on the magnetic surfaces Ψ. These are energy density flux $E(\Psi)$, angular momentum density flux $L(\Psi)$, angular velocity $\Omega_F(\Psi)$, entropy $s(\Psi)$, and the ratio of magnetic flux to particle number density flux $\eta(\Psi)$. These integrals are defined at the outflow base and must obey the conditions of a smooth passage of the critical surfaces.

The jet current is defined as

$$\frac{I}{2\pi} = \frac{L - \Omega_{\rm F} r^2 E/c^2}{1 - \Omega_{\rm F}^2 r^2/c^2 - \mathcal{M}^2}$$

It depends on the particular jet structure as well as the integrals. We set the condition of a current closure inside a jet by prescribing $L(\Psi_{tot}) = 0$ and $\Omega_F(\Psi_{tot}) = 0$, where Ψ_{tot} is a total magnetic flux:

$$L(\Psi) = \frac{\Omega_0 \Psi}{4\pi^2}\sqrt{1 - \frac{\Psi}{\Psi_{\rm tot}}},$$

$$\Omega_{\rm F}(\Psi) = \Omega_0\sqrt{1 - \frac{\Psi}{\Psi_{\rm tot}}}.$$

The energy integral is chosen in a form

$$E(\Psi) = \Omega_{\rm F} L + \mu_0 \eta \gamma(\Psi)$$

Where the relativistic enthalpy $\mu_0 = m_{\rm p}c^2 + m_{\rm p}w_0$ is defined as a function of a sonic velocity at the jet boundary $w_0 = c_0^2/(\Gamma - 1)$ [2].

Such a choice of integrals ensures that not only toroidal magnetic field vanishes at the jet boundary, but the poloidal as well. So, we construct a jet with a zero magnetic pressure at the very jet boundary.

In order to balance the outer pressure we introduce the finite outflow temperature. We show that in the entire jet volume the thermal pressure is negligible in comparison with the magnetic one for the realistic parameters. On the other hand, at the jet boundary, where the toroidal and poloidal magnetic fields vanish, the enthalpy term in the energy density flux provides the necessary thermal pressure.

The solution is obtained by the iterative procedure, where for a given fast Mach number at the jet axis we find the unique self-consistent solution up to the jet boundary, defined by the condition $\Psi(r_{jet}) = \Psi_{tot}$.

As a result for each given distance *r* along the jet we obtain the jet width *d* as a function of the outer pressure *P*. The result is presented in Figure 1 for different magnetization parameters σ_M [5] at the jet base.

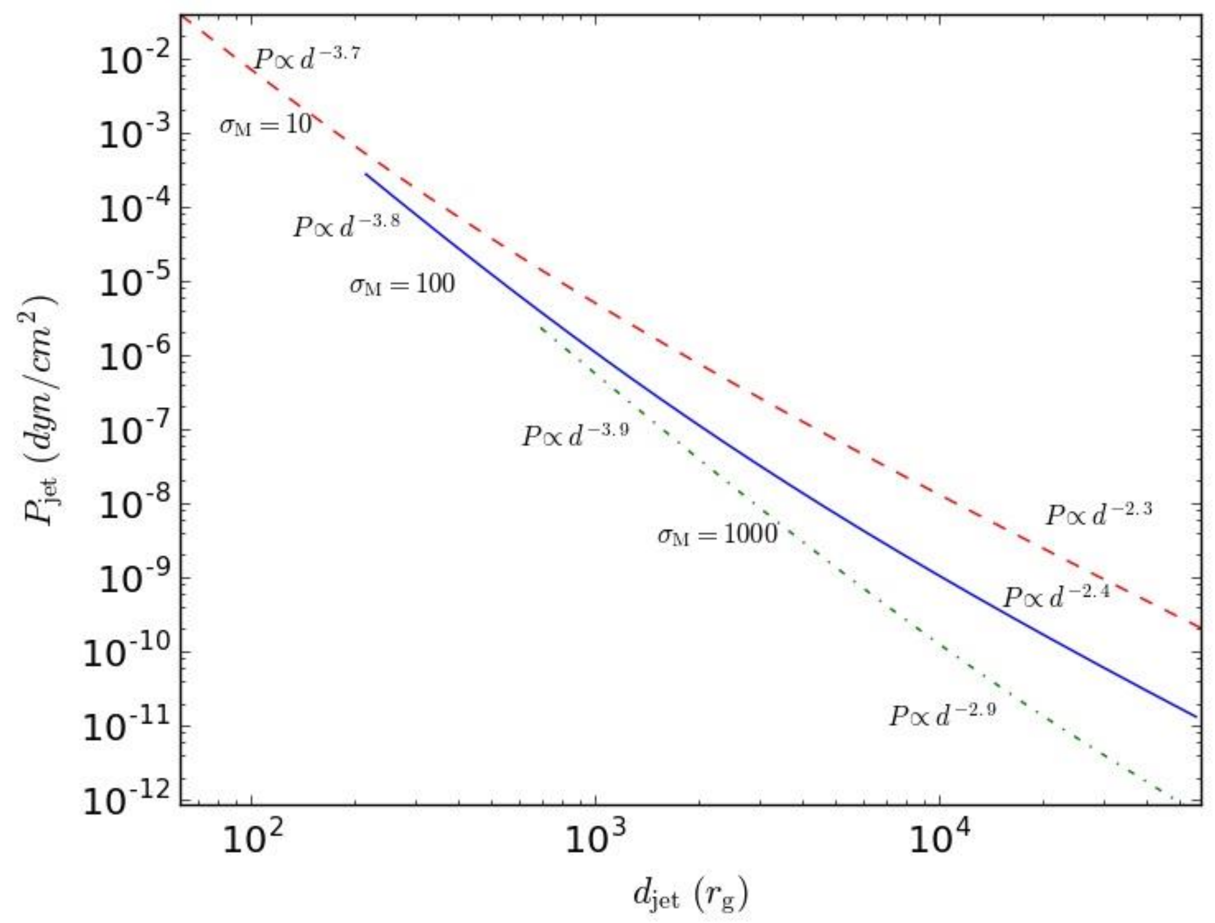

Figure 1. The outer pressure P_{jet} magnitude as a function of a jet radius d. Red curve corresponds to $\sigma_M = 10$, blue – to $\sigma_M = 100$, green – to $\sigma_M = 1000$. The left starting point of each curve corresponds to a super-Alfvenic flow start at the jet axis.

3. Estimating the jet parameters using the jet shape break – M87

We propose that the change in a jet shape may be not due to change in a pressure profile, as suggested by [1], but due to change in a jet intrinsic properties – the flow transition from the magnetically-dominated to the equipartition regime (see Figure 2). If this interpretation is valid, than the observation of such a jet shape change may provide us the additional information about jet parameters. Here we find the parameters for M87 – the rotation parameter, the total magnetic flux in a jet, and the total jet power.

We model the outer pressure profile by the Bondi accretion model [e.g., 4] as $P = P_0(r/r_0)^{-2.5}$. The pressure profile together with the obtained dependence $P(d_{jet})$ provides the jet boundary shape $r(d)$. In numerical calculations the pressure is normalized by the value

$$p_0 = \left(\frac{\Psi_0 a^2}{2\pi r_g^2 \sigma_{\rm M}}\right)^2$$

and the distances are normalized by the light cylinder radius $R_L = \frac{c}{\Omega_F} = \frac{r_s}{a}$.

For M87 there are two pressure magnitude measurements on kpc scales. We use here the later result by [7]: at $r = 120$ pc pressure $P = 1.9 \times 10^{-9}\, dyn \cdot cm^{-2}$. The pressure is measured up to approximately Bondi radius, with the pressure profile outside it estimated by $P \propto r^{-1}$. However, inside the Bondi radius the pressure profile is not known, so we imply here the "Bondi" power -2.5. This power provides the initial jet boundary form as $r \propto d^{1.51}$ and further the conical form $r \propto d^{1.1}$ (Figure 3), the powers being close to the ones obtained by [1], which are 1.73 and 0.96.

For a prescribed initial magnetization σ_M we may find the total magnetic flux Ψ_{tot} and the rotation rate a to fit the position of a change in a jet shape. The results are: $a = 0.13$, which for the maximal power condition [3] $\Omega_F = \Omega_H/2$ corresponds to BH spin parameter $a_* = 0.81$, close to maximum angular momentum with $a_* = 1$. The total magnetic flux needed to explain the position of a jet shape break is $\Psi_{tot} = 10^{34.5}\, G \cdot cm^2$. For the electromagnetic energy losses model the corresponding total jet power is $P_{tot} = 1.6 \times 10^{42} \div 1.3 \times 10^{43}\, erg \cdot s^{-1}$ depending on the different estimates.

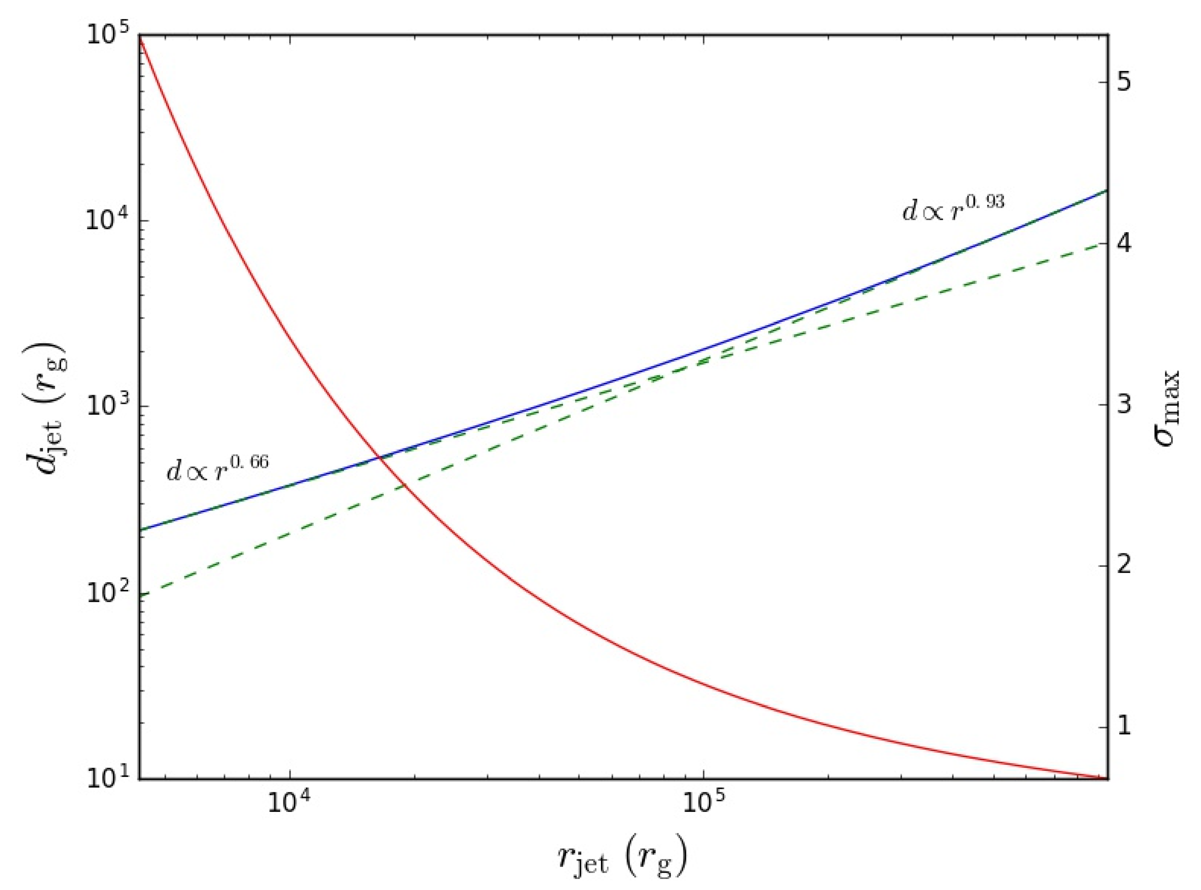

Figure 2. The predicted jet shape (blue) for the pressure profile $P_{jet} \propto r^{-2.5}$, which corresponds to the Bondi accretion. The red curve is a maximal flow magnetization for the given distance r_{jet} along the jet. The jet shape break roughly corresponds to a transition from the magnetically-dominated ($\sigma_{max} \gg 1$) to equipartition regime ($\sigma_{max} \approx 1$).

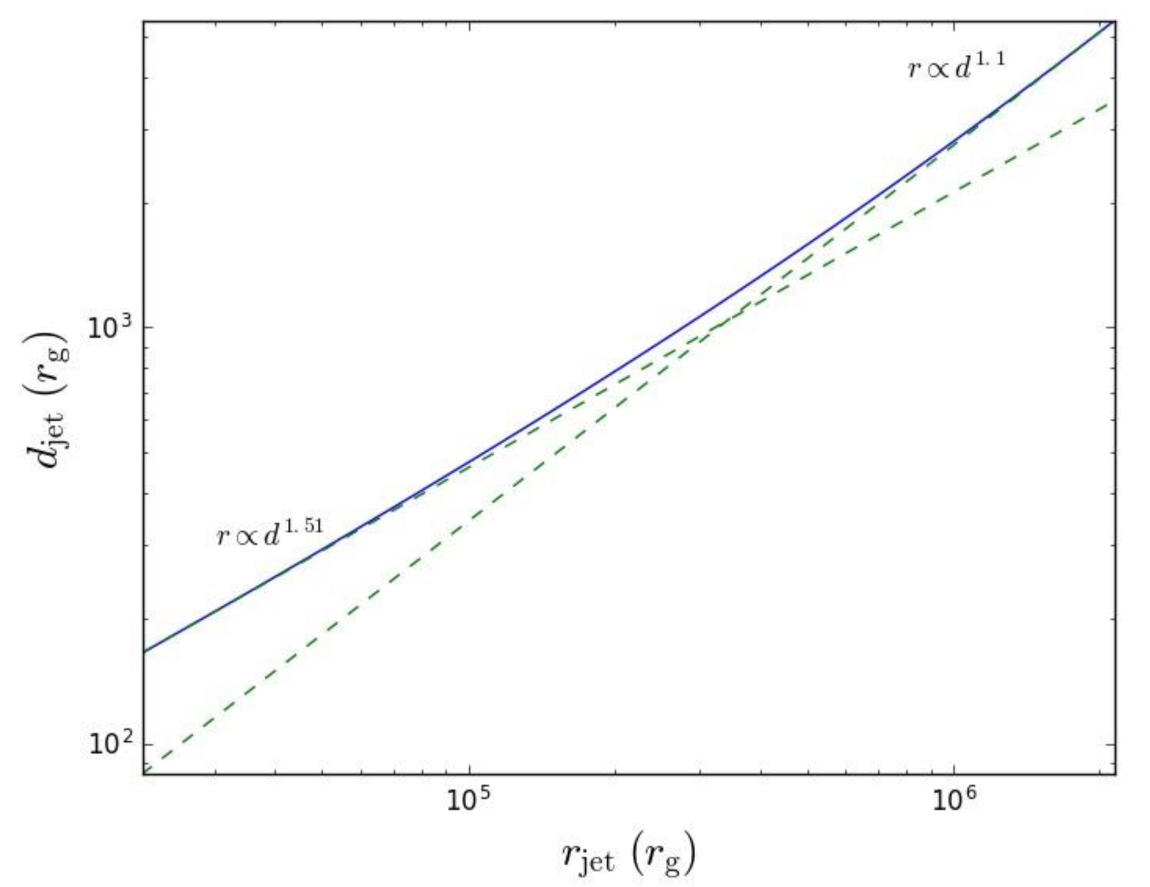

Figure 3. The fit of M87 jet shape break.

The presented jet model allows to reproduce the change in a jet shape for the universal pressure profile along a jet (e.g. predicted by Bondi accretion model) due to change in a jet intrinsic state – the transit from magnetically-dominated to equipartition regime. This interpretation together with the measurements of a jet shape break position yields an instrument to estimate such parameters as a jet rotation rate, a total magnetic flux, and a total jet power. Applied to M87 jet the obtained parameters seem reasonable. It is possible to apply the method for other sources with measured jet shape [6].

4. References

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