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Analytical Solution of Magnetically Dominated Astrophysical Jets: Jet Launching, Acceleration, and Collimation

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Jets are ubiquitously in association with different celestial objects from young stellar objects to active galactic nuclei[1]. The jet fluid forms a narrow beam and ejects itself from a "small" celestial space, just like a "lightsaber" breaks into the deep universe. The longest jet can reach a range 10 billion times longer than its initial radius, and the maximum jet velocity can reach up to 99.99% of the speed of light. The process of how jet launching, acceleration and collimation is still unclear.

The magnetic field plays an important role in the process of jet launching, acceleration and collimation[2-3]. The magnetic dominated jet plasma continuously converts the Poynting energy flow into the kinetic energy of the fluid, accelerating and collimating the jet. In the case of very high magnetization, where the force-free approximation holds, the radial dynamic equilibrium of magnetically dominated jet is measured by the so-called the "pulsar equation". This equation is usually solved numerically. Inspired by recent numerical simulations[4], we separated "pulsar equation" into a rotating and a nonrotating term[5]. We find that the two equations with either term can be solved analytically, and the two solutions match each other very well. Therefore, we obtain a general approximate solution of a magnetically dominated jet. Based on this solution, a general analytical jet model can be constructed, which quantitatively descries the properties of magnetic dominated jet flow (including the 3D distribution of magnetic field, velocity, density, current and charge). For example, the jet acceleration includes three stages. (1) The jet flow located within the Alfvén critical surface (ACS, i.e., the light cylinder) has a nonrelativistic speed, and is dominated by toroidal motion. (2) The jet is beyond the ACS where the flow is dominated by poloidal motion and becomes relativistic. The total velocity in these two stages follows the same law $v\Gamma \approx \Omega R$. (3) The evolution law is replaced by $v\Gamma \approx 1/\left(\theta\sqrt{2-\nu}\right)$, where θ is the half-opening angle of the jet and $0 \le \nu \le 2$ is a free parameter determined by the magnetic field configuration. This is because the earlier efficient acceleration finally breaks the causality connection between different parts in the jet, preventing a global solution.

The analytical model based on this solution is consistent with previous theories[6-10] and can explain the main results of jet observation, such as jet shape configuration (quasi-parabolic shape), acceleration profile (from non-relativistic to relativistic), and polarization pattern (helical magnetic field) etc. Furthermore, the solution is applicable to, e.g., limb-brightening (a hollow jet), periodical variability (a helical jet), and "complex" proper motion pattern (a stratified jet structure) etc. In this talk, I will present the details of the theory, examples of comparing with observations, and some predictions.

References:

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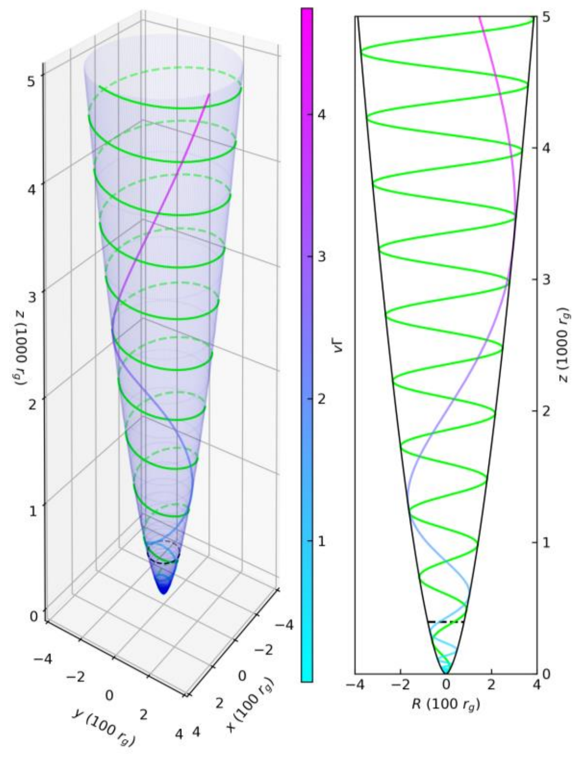

Figure. Configuration of a jet magnetic stream surface (illustrated by the light blue semitransparent surface in the left panel) threading the equator of a black hole with a spin dimensionless parameter $a = 0.1$: the green line represents the magnetic field line and the gradient colored line represents the trajectory of the jet fluid with colors measuring the value of the four-velocity $v\Gamma$ of jet flow. The right panel is a 2D projection as seen edge-on of the left 3D configuration panel. The black dashed line shows the ACS ($z \approx 400\ r_g$).