Using plasma jets to simulate galactic outflows*

D.D. Ryutov

Lawrence Livermore National Laboratory, Livermore, CA 94551

Presented at the Plasma Jet Workshop, Los Alamos, January 24,25, 2008

____

* Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

Galactic and extragalactic jets are among the most spectacular astrophysical phenomena

J. Wiseman, J. Biretta. “What can we learn about extragalactic jets from galactic jets?” New Astronomy Reviews, 46, 411, 2002

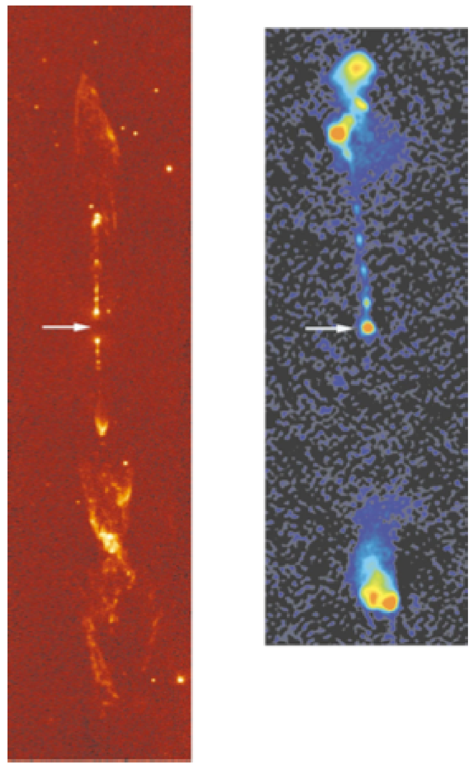


Fig. 1. (Left) The HH212 protostellar jet. HH 212 is highly embedded and thus is visible only in infrared 2.12 μm H_2 shock emission (Zinnecker et al., 1998). The let length is about 0.5 parsec. Note the symmetric and quasi-periodic structure of shock knots along the jet axes. (Image provided by M. McCaughrean); (Right) The quasar jet source 3C204 (Bridle et al., 1994). The overall length is about 160 kiloparsecs. Note the periodic knots, possibly shocks, along the visible jet. Arrows indicate location of the ‘engine’ powering the source.

There have been numerous HEDP-based studies of astrophysical jets carried out during the last decade:

J.M. Foster, B.H. Wilde, P.A., et al. “High-energy-density laboratory astrophysics studies of jets and bow shocks.” Astrophys. J. Letters, **634**, L77, 2005.

S.V. Lebedev, A. Ciardi, D.J. Ampleford, et al. “Magnetic tower outflows from a radial wire array Z-pinch.” Monthly Notices of the Royal Astronomical Society, **361**, 97, 2005.

D.J. Ampleford, S.V. Lebedev, A. Ciardi et al. “Supersonic radiatively cooled rotating flows and jets in the laboratory.” PRL, January 2008.

U. Shumlak, B.A. Nelson, B. Balick. “Plasma jet studies viavia the flow Z-pinch.” Astrophys. Space Sci., **307**, 41, 2007.

There have been numerous HEDP-based studies of astrophysical jets carried out during the last decade:

J.M. Foster, B.H. Wilde, P.A., et al. “High-energy-density laboratory astrophysics studies of jets and bow shocks.” Astrophys. J. Letters, **634**, L77, 2005.

S.V. Lebedev, A. Ciardi, D.J. Ampleford, et al. “Magnetic tower outflows from a radial wire array Z-pinch.” Monthly Notices of the Royal Astronomical Society, **361**, 97, 2005.

D.J. Ampleford, S.V. Lebedev, A. Ciardi et al. “Supersonic radiatively cooled rotating flows and jets in the laboratory.” PRL, January 2008.

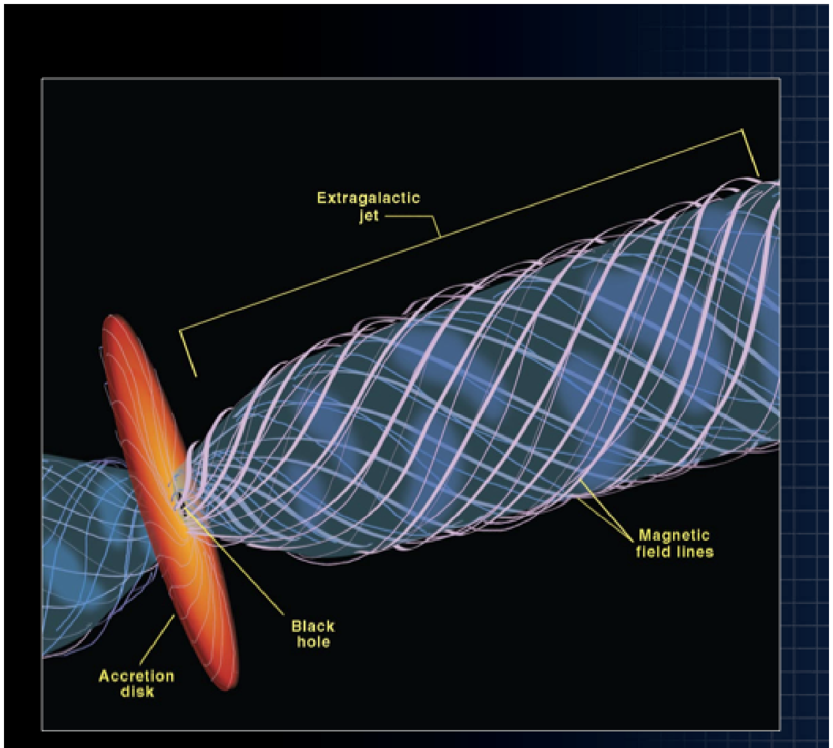
U. Shumlak, B.A. Nelson, B. Balick. “Plasma jet studies viavia the flow Z-pinch.” Astrophys. Space Sci., **307**, 41, 2007.

Scalability issues have been considered in:

D.D. Ryutov, R. P. Drake, J. Kane, E. Liang, B. A. Remington, and W.M. Wood-Vasey. “Similarity criteria for the laboratory simulation of supernova hydrodynamics.” Astrophysical Journal, v. 518, p. 821 (1999).

D.D. Ryutov, B.A. Remington, H.F. Robey, R.P. Drake. “Magnetohydrodynamic scaling: from astrophysics to the laboratory,” Phys. Plasmas, 8, 1804, May 2001.

Differentially rotating accretion disc is thought to be a key player in the formation of both galactic and extragalactic jets



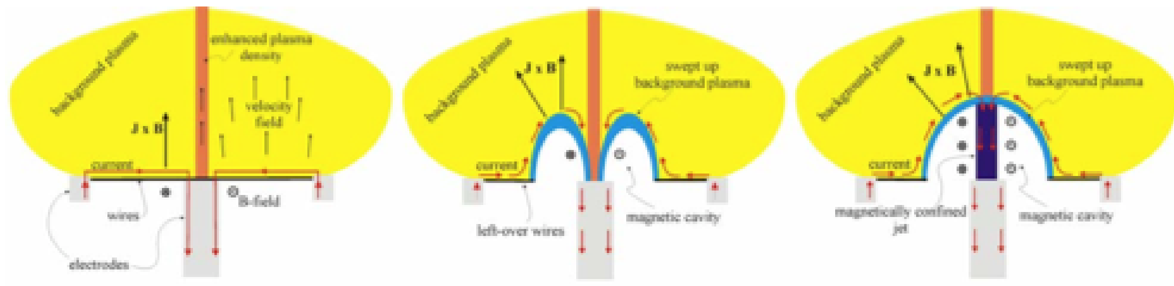
Schematic structure of the core of an active galaxy. (Illustration credit: John Biretta.)

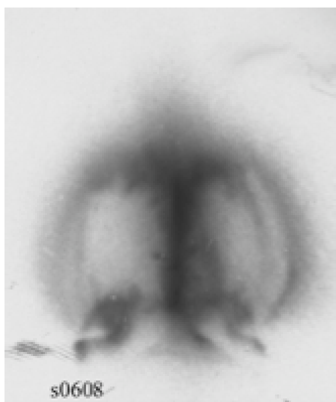
Differential rotation creates a strong toroidal magnetic field which pushes the material in the vicinity of the "central engine" up and down with respect to the plane of the disc.

A current pattern is formed, in which the current flows along the axis and returns over a much larger surface (a "cocoon" structure).

Illustration from http://www.aoc.nrao.edu/pr/m87.collimation.html

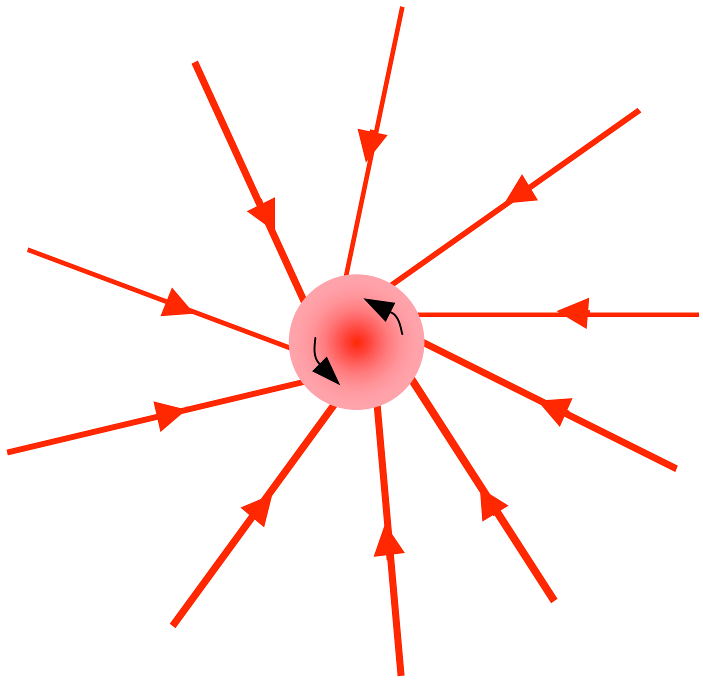
“Magnetic tower jets” were studied with the MAGPIE Z-pinch facility (London, UK)



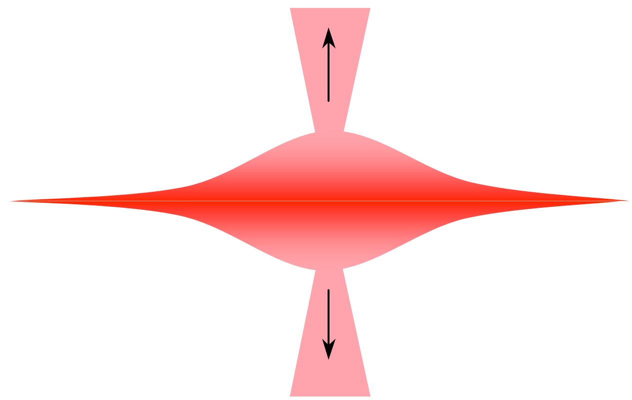


S.V. Lebedev, A. Ciardi, D.J. Ampleford, et al. “Magnetic tower outflows from a radial wire array Z-pinch.” Monthly Notices of the Royal Astronomical Society, **361**, 97, 2005.

An array of plasma jets of the type described by Witherspoon et al* would allow one to imitate the formation of a differentially rotating disc (something that hasn't been done before)



Top view



Side view

*A. Case, F. D. Witherspoon, et al. "Dense Hypervelocity Plasma Jets." Bull. Am. Phys. Soc., v. 52, #16, p.250; S.J. Messer, F.D. Witherspoon, et al. "Probe Measurements on the HyperV Plasma Gun." ." Bull. Am. Phys. Soc., v. 52, #16, p.250.

Expected plasma parameters for an array of 12 jets forming a 20 cm diameter disc

Plasma parameters in the disc:

n=$3 \cdot 10^{15}$ cm^{-3}; T=10 eV; disc radius r=10 cm; rotation velocity at the periphery v_{rot}=$5 \cdot 10^{6}$ cm/s

Plasma parameters in the outflow:

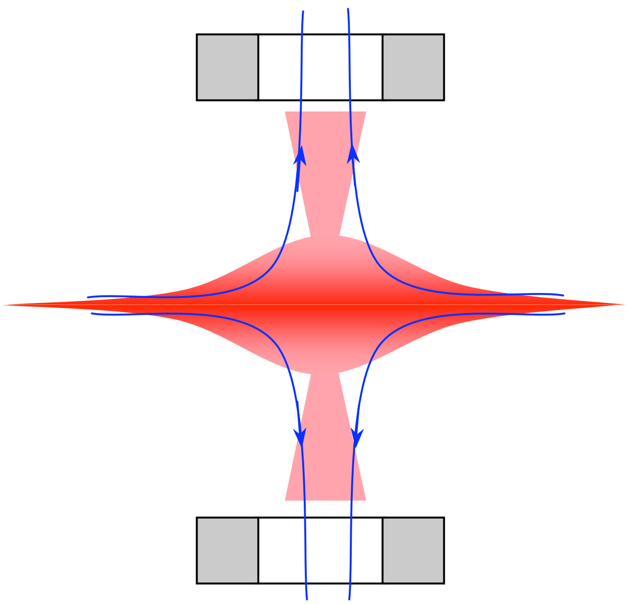
n_{jet}=$3 \cdot 10^{15}$ cm^{-3}; T_{jet}=10 eV; minimum radius r_{jet}=5 cm; vertical velocity v_{jet}=$5 \cdot 10^{6}$ cm/s

Derived parameters:

Plasma kinematic viscosity $\nu \sim 2 \cdot 10^{5}$ cm^{2}/s; Reynolds number $Re \equiv r v_{rot}/\nu \sim 250$

In astrophysical case, the plasma is collisional due to very large length-scale (~ parsec for Young Stellar Outflows). Plasma parameters in the typical Herbig-Haro object: r_{jet}=$3 \cdot 10^{17}$ cm; v_{jet}=$2 \cdot 10^{7}$ cm/s; T_{jet}~ 20 eV; n_{jet}=10-100 cm^{-3}; $Re \equiv r_{jet} v_{jet}/\nu \sim 10^{3} - 3 \cdot 10^{4}$

Impose a weak cusp magnetic field to see a conversion of the poloidal field into toroidal field by the differential rotation



Magnetic diffusivity for the aforementioned plasma parameters:

$D_{magn} \sim 10^5$ cm^2/s

Magnetic Reynolds number:

$Re_m \equiv rv_{rot}/D_{magn} \sim 500$

How could the experimental information be used?

1. Benchmark 3D astrophysical codes in the relevant range of dimensionless parameters

2. Vary the parameters and geometry at will; collect large statistics (in particular, vary the ratio of the ambient plasma density to that in the jet; use gas-puffs? add higher-Z impurities to enhance radiative losses?)

3. Generate internal slow shocks in the outflow

4. Obtain morphologically relevant pictures; show the ability to modify them by controlling the parameters and orientation of jets