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Experiments and models of MHD jets and their relevance to astrophysics and solar physics[1]

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MHD-driven flows exist in both space and lab plasmas because the MHD force-balance equation $\mathbf{J} \times \mathbf{B} - \nabla \mathbf{P} = \mathbf{0}$ can only be satisfied in situations having an unusual degree of symmetry. In the normal situation where such symmetry does not exist, an arbitrary magnetic field $\mathbf{B}$ and its associated current $\mathbf{J} = \mu_{\mathbf{0}}^{-\mathbf{1}} \nabla \times \mathbf{B}$ provide a magnetic force $\mathbf{F} = \mathbf{J} \times \mathbf{B}$ having the character of a torque, i.e., $\nabla \times\ \mathbf{F} \neq \mathbf{0}$. Because $\nabla \times \nabla P = 0$ is a mathematical identity, no pressure gradient can balance this torque so a flow is driven. Additionally, since ideal MHD has magnetic flux frozen into the *frame* of the moving plasma, the flow convects frozen-in magnetic flux. If the flow slows and piles up, both the plasma and the frozen-in magnetic flux will be compressed. This magnetic flux compression amplifies both the frozen-in $\mathbf{B}$ and its associated $\mathbf{J}$. Slowing down thus increases certain components of $\mathbf{F}$, in particular the pinch force associated with the electric current in the flow direction. This increased pinching causes the flow to self-collimate if the leading edge of the flow moves slower than the trailing part so there is compression in the flow frame. The result is that the flow self-collimates and forms a narrow jet. Self-collimating jets with embedded electric current and helical magnetic field are analogous to the straight cylindrical approximation of a tokamak, but now with the length of the cylinder continuously increasing and the radius depending on axial position. The flows are directed from axial regions having small radius to axial regions having large radius. The flow velocity is proportional to the axial electric current and is a significant fraction of the Alfvén velocity. Examples of these MHD-driven flows are astrophysical jets, certain solar coronal situations, and the initial plasma produced by the coaxial magnetized plasma guns used for making spheromaks. The above picture has been developed from laboratory measurements, analytic models, and numerical simulations. Upon attaining a critical length, laboratory jets develop a complex but resolvable sequence of instabilities which is effectively a cascade from the large-scale MHD regime to the small-scale two-fluid and kinetic regimes. This cascade involves kinking, Rayleigh-Taylor instabilities, magnetic reconnection, whistler waves, ion and electron heating, and generation of hard X-rays. An extended model shows how clumps of particles in a weakly ionized accretion disk move like a metaparticle having its charge to mass ratio reduced from that of an ion by the fractional ionization. These weakly charged metaparticles follow an inward spiral trajectory that is neither a cyclotron nor a Kepler orbit and accumulate at small radius where they produce a disk-plane radial EMF that drives astrophysical jets.

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