

## Laboratory Plasma Source as an MHD Model for Astrophysical Jets: Final Report for NAGW-4869

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The extremely versatile magnetized coaxial gun (MCG) experimental facility, CPS-1 (Coaxial Plasma Source), is capable of producing highly conducting, high enthalpy, magneto-flows in a widely varied applied magnetization. This device provides an excellent test bed to examining the interaction of a variety of magneto-flows with applied and self magnetization, and illustrating mechanisms for axial mass ejection, flow interaction with background neutral gas, and turbulent accretion of astropasmas. In addition to standard plasma diagnostic techniques allowing the elucidation of gross MHD behavior and stability, we have recently developed techniques allowing the direct investigation on the effects of micro-turbulence on these flow streams and their interaction with magnetic fields.

The significance of the work herein lies in the demonstration of laboratory MCG devices like CPS-1 to produce energetic magneto-flows with embedded magnetic fields that can be used as a simulation tool to study flow interaction dynamics of astro-jet flows, to demonstrate the magnetic acceleration and collimation of flows with primarily toroidal fields, and study cross field transport in turbulent accreting flows. Since plasmas produced in MCG devices have magnetic topology and magnetohydrodynamic (MHD) flow regime similarity to stellar and extragalactic jets, we expect that careful investigation of these flows in the laboratory will reveal fundamental physical mechanisms influencing astrophysical flows. Discussion herein focuses on recent results describing collimation, leading flow surface interaction layers, and turbulent accretion.

The study objectives for a new research effort would be to develop and employ novel electrostatic, magnetic, and visible plasma diagnostic techniques to measure plasma and flow parameters of the CPS-1 device in the flow chamber downstream of the plasma source to study, (1) mass ejection, morphology, and collimation and stability of energetic outflows, (2) the effects of external magnetization on collimation and stability, (3) the interaction of such flows with background neutral gas, the generation of visible emission in such interaction, and effect of neutral clouds on jet flow dynamics, and (4) the cross magnetic field transport of turbulent accreting flows.

The applicability of existing laboratory plasmas facilities to the study of stellar and extragalactic plasmas should be exploited to elucidate underlying physical mechanisms that cannot be ascertained through astrophysical observation, and provide baseline to a wide variety of proposed models, MHD and otherwise. The work proposed herein represents a continued effort on a novel approach in relating laboratory experiments to astrophysical jet observation. There exists overwhelming similarity among these flows that has already produced some fascinating results and is expected to continue a high pay off in further flow similarity studies.

## 1. Introduction

Astrophysical jets are a diverse group of celestial objects that are generally accepted to be energetic outflows from a variety of sources[1]. The feature central to all such objects is an extremely well collimated emission map first observed in the radio range with an electron cyclotron signature from radio galaxies suggesting that such flows are magnetized[1,2]. In this largest class of jets (radio jets or double lobed radio galaxies), the emission profile points back to the galactic center where the nucleus of the active galaxy (AGN) appears to be the source of the flow. On a much smaller scale, young stellar objects (YSO) emit jets which terminate in visibly bright objects (some of which are classified as HH objects[1]). In some cases the jet itself is observed in the visible (Fig. 1). Zeeman measurements in the molecular cloud cores associated with YSO outflows support the presence of magnetic fields there also.

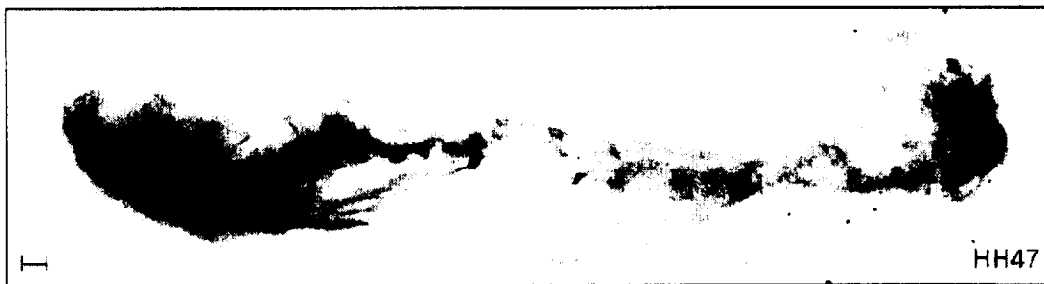


Figure 1: Visible Jet in HH47

It is well agreed upon that there are several ingredients necessary to produce astrophysical jets. The source of energy for the flow originates in the central massive object acting as prime mover[1-3]. In the case of a YSO jet, the prime mover is likely a proto-star of order  $M_{\odot}$ , while an AGN source may be as large as  $10^8 - 10^9 M_{\odot}$ . Interstellar material is drawn by the central object through the accretion process, the inner parts of an accretion disk may be ionized and channeled into a flow along the symmetry axis in a jet. As such, jets may be a natural consequence of star formation and dense galactic cores. In fact, jets may well be produced in all YSO and AGNs, and it is merely extinction and quenching that prevents observation. How such flows are established and how they interact with their surroundings are not at all well understood, and are the subjects of this and many other investigations.

We recently became intrigued by some obvious observational similarities between the high enthalpy plasma flows we have been producing in our magnetized coaxial gun (MCG) source[4] for advanced propulsion studies[5] and those from a variety of astrophysical objects classified as jets[1,3]. Though rather disparate on spatial and temporal scales, both flows show the similar gross flow feature of a directed high enthalpy plasma stream flow that remains well collimated for many characteristic source dimensions in linear extent and many dynamical times downstream of the source. Further, the observation of strong magnetization in the astrophysical counterpart reveals the potential dynamical importance of magnetic fields in astrojets, yet another strong connection to the laboratory model that is solely driven by magnetohydrodynamic (MHD) forces. Many in the astrophysics community indeed favor MHD mechanisms for forming, accelerating, and collimating jets. Aside from the omnipresence of strong fields in jet flows, MHD is favored for its recognized ability to collimate plasma flows through pinch forces, to accelerate plasma to high speeds, and the efficacy with which magnetic fields extract angular momentum from rotating plasma accretion disks presumed to be the source of the jet plasma.

What's more, mechanisms alternative to MHD do not appear to satisfy all the observations[1]. For example radiation pressure seems implausible as an acceleration mechanism because of the low luminosity of many sources. With the exception on SS433, all jet sources (AGN and YSO) exhibit emission well below the

Eddington luminosity. A related mechanism is the hot plate. This too suffers as an acceleration mechanism for several reasons including; radiation drag, lack of a good collimation mechanism, and the requirement that the wind opacity be greater than that of the accretion disk. Since the disk is the source of the jet outflow, it seems unlikely that radiation coupling in this manner is the sole mechanism responsible for jet acceleration. Hydrodynamic nozzles are also proposed wherein ambient medium kinetic pressure adiabatically forces jet exhaust through a constriction much like a rocket nozzle. However, collimation of such flows far down stream from the source is questionable, and too, small scale collimation near the source requires such large pressure that radiation cooling would be catastrophic. Geometric distortions near the event horizon for massive sources (like those for AGN and XRB) can create funnels which can guide the flow along the symmetry axis. Yet, global instabilities are expected to destroy these flows in several dynamical time scales, a mechanism further exacerbated by hydrodynamic stresses. As well, funneled jet flow velocities are limited to well below those required for superluminal observations. The funnel mechanism also would be inapplicable to YSO jets. Hence, the process of elimination rules out all but magnetic acceleration as the drive mechanism for both AGN and YSO jets. Moreover, if we accept that these two types of jets (from YSO and AGN which make up the bulk of things that are called jets) are driven by the same mechanism, then there are several other effects which we can exclude as coincidental but un-important; black holes and relativistic effects, rotation at breakup speeds, and details of the disk-star boundary layer.

We currently possess an extremely versatile MCG experimental facility, CPS-1 (Coaxial Plasma Source)[4], capable of producing highly conducting, high enthalpy, magneto-flows in a widely varied applied magnetization. This device provides an excellent test bed to examining the interaction of a variety of magneto-flows with applied and self magnetization, and illustrating mechanisms for axial mass ejection, flow interaction with background neutral gas, and turbulent accretion. In addition to standard plasma diagnostic techniques allowing the elucidation of gross MHD behavior and stability, we have recently developed techniques allowing the direct investigation on the effects of micro-turbulence on these flow streams and their interaction with magnetic fields[6].

The significance of the work described herein lies in the demonstration of Magnetized Coaxial Plasma Gun (MCG) devices like CPS-1 to produce energetic laboratory magneto-flows with embedded magnetic fields that can be used as a simulation tool to study flow interaction dynamics of jet flows, to demonstrate the magnetic acceleration and collimation of flows with primarily toroidal fields, and study cross field transport in turbulent accreting flows. Since plasmas produced in MCG devices have magnetic topology and MHD flow regime similarity to stellar and extragalactic jets, we expect that careful investigation of these flows in the laboratory will reveal fundamental physical mechanisms influencing astrophysical flows. Discussion in the next section (sec. 2) focuses on recent results describing collimation, leading flow surface interaction layers, and turbulent accretion.

The primary objectives for a new three year effort would involve the development and deployment of novel electrostatic, magnetic, and visible plasma diagnostic techniques to measure plasma and flow parameters of the CPS-1 device in the flow chamber downstream of the plasma source to study, (1) mass ejection, morphology, and collimation and stability of energetic outflows, (2) the effects of external magnetization on collimation and stability, (3) the interaction of such flows with background neutral gas, the generation of visible emission in such interaction, and effect of neutral clouds on jet flow dynamics, and (4) the cross magnetic field transport of turbulent accreting flows.

The applicability of existing laboratory plasmas facilities to the study of stellar and extragalactic plasmas should be exploited to elucidate underlying physical mechanisms that cannot be ascertained through astrophysical observation, and provide baseline to a wide variety of proposed models, MHD and otherwise. The work proposed herein represents a continued effort on a novel approach in relating laboratory experiments to astrophysical jet observation. There exists overwhelming similarity among these flows that has already produced some fascinating results and is expected to continue a high pay off in further flow similarity studies.

## 2. Study Results

Recent efforts have been committed in an experimental effort to diagnose plasma flow features from a magnetized coaxial plasma gun (MCG) source (CPS-1 at NCSU)[4] so that we may establish the applicability of such sources as laboratory models for astrophysical flows. The experimental work in electrostatic plasma sensor development, experiment preparation, data collection, and data analysis has been performed by graduate student, Ms. Rebecca Caress (now at United Defense), who engaged in this effort for a Master of Science project, and myself. Our efforts were well complemented by the flow channel magnetics work of Dr. Dorwin C. Black (now at NRL), a former PhD graduate student in the NCSU plasma sciences program who recently completed his dissertation work on plasma flow channel physics. In addition, continual contact with the astrophysics community, primarily through Dr. John Contopoulos (Univ. of Chicago) and the astrophysics group at NCSU, have provided extremely valuable guidance in understanding the important features of astrojet flows and contemporary MHD computer modeling of such.

Following a brief discussion of experimental facilities, three detailed sets of experimental observations of magnetized plasma flows from the CPS-1 MCG source will be described: two dimensional plasma flow morphology, interaction layers where energetic plasma pushes up against cold neutral gas (with features very similar to interaction layers in jets and molecular outflows), and magneto-turbulent accretion where convective plasma transport is described in the presence of applied magnetization including micro-turbulence enhancements to resistive diffusivity (having features similar to those required in some magnetized disk accretion models). For each of these subjects the experimental observations will be first described, followed by a discussion of the relevance to jets, and concluded by a brief discussion of future measurements required to further explore these subjects.

## 2.1. Experimental Facilities

The CPS-1[4] is a device in the classification of magnetized coaxial plasma guns (MCG). MCG sources consists of a coaxial arrangement of discharge electrodes between which a high temperature plasma is initiated in pre-fill or injected gas (1-400 mTorr, He) by the application of a high voltage from a capacitive energy source. The discharge is accelerated along the coaxial channel under the influence of the radial discharge current interaction with the self azimuthal magnetic field, thus producing high energy magnetosonic flows. In its present configuration, the CPS-1 device can produce plasma discharges with parameters in the range 10-50 eV,  $10^{14} - 10^{15} \text{ cm}^{-3}$ , and  $\sim 10^7 \text{ cm/s}$ , as measured with electrostatic probes, in plasmas with discharge currents of 120 kA and electrode potential differences of 0.5 - 1.0 kV. External magnetization with a solenoid coil provides a poloidal field that links the discharge electrodes for the study of flow/field interactions within the channel, and for plasma stream flow control outside the source. The diverging applied field outside the source may accelerate the flow through magnetic nozzling while also diverting the flow to a more diffuse flow stream. Jet morphological comparisons are made both with and without external applied field.

Figure 2 shows a schematic of the CPS-1 plasma and a simplified conceptualization of the plasma flow stream as it exits the gun muzzle in a self-formed magnetic nozzle-like configuration. The distorted, and truncated applied field lines shown here are displayed for conceptual purposes only (to visualize the self-formed flow channel only). In quasi-steady-state operation, plasma is created in the upstream (breech) region of the gun (near the insulator) by discharge of a capacitive energy storage system, and simultaneously accelerated to the local drift velocity. The applied  $B_{r,z}$  flux (generated by a solenoid inside the cathode) emerges from the front of the cathode and returns along the inside of the anode. In typical MCG operating conditions, this applied flux persists for a time duration (several ms) which is long compared to the discharge time of 0.1 - 0.5 ms. The initial flow entrains additional magnetofluid as it ionizes more neutral gas. Thermalization quickly follows as the flow drifts from the entrainment point in the breech to the muzzle. As the axial plasma flow enters the constriction in the downstream (muzzle) end of the MCG, it can be accelerated further by the converging-diverging magnetic nozzle in magnetized operation. The nozzle, roughly defined by the  $B_{r,z}$  lines of force in Fig. 2, is established by radial force balance between the self ( $B_\theta$ ) and applied ( $B_{r,z}$ ) field pressures. The self field decreases from its upstream value as a result of the conversion of field energy into mass flow energy. This allows the magnetoplasma to be radially constricted by the applied field, thus forming the converging part of the self-formed magnetic nozzle. This naturally invokes an assumption of ideal MHD since plasma diffusion across the applied field during the acceleration (run down) time is not allowed in this simple conceptualization. Finally, the expansion of the ( $B_{r,z}$ ) field as it leaves the MCG allows for magnetoplasma expansion, creating the diverging nozzle flow and additional velocity gain.

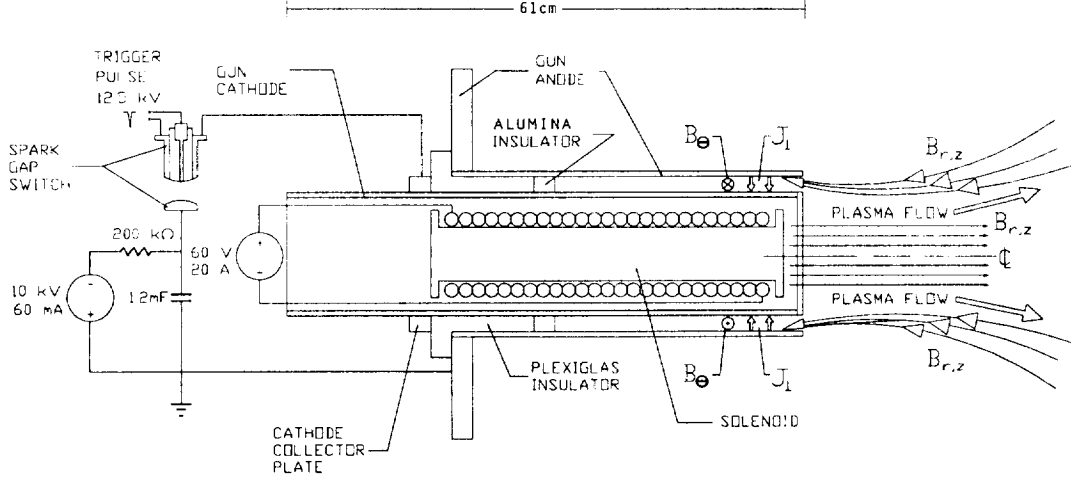


Figure 2: Schematic of the CPS-1 MCG hardware and plasma stream flow.

In a more realistic description that includes finite resistivity, the magnetoplasma does somewhat distort the applied field as it diffuses through, but does not distort the applied field indefinitely as depicted above. The flow may still be nozzled, however, as the magnetofluid flow passes through a constriction provided by the applied field magnetic pressure[7-9].

## 2.2. Flow Morphology

Flow morphology of CPS-1 plasma discharges was mapped using a quadrupole Langmuir (electrostatic) probe[10,11] (Fig. 3). This measurement technique yields simultaneous electron temperature and density, as well as flow speed and electrostatic floating potential. Data were recorded at 50 spatial locations in the CPS-1 vacuum chamber from as many separate discharges. Reproducibility was checked at each location and found to be better than 20% in most cases. Figure 4 displays such a data set showing plasma electron temperature (eV), density ( $\text{cm}^{-3}$ ), axial flow speed (cm/s), and plasma kinetic pressure (Pa) contours in the vacuum chamber outside the MCG source for discharges in which the CPS-1 external magnetization (solenoid coil) was not energized. In this class of discharges, the only source of magnetization of the plasma is the self field ( $B_\theta$ ) generated by internal plasma currents which result in almost entirely azimuthal fields. For sake of distinction, we term these unmagnetized discharges to avoid confusion with discharges that do employ external applied fields. The position of centerline-muzzle is at the origin in this figure. The annular channel centerline is at roughly 8.25 cm and the axial position advances away from the source. These data exhibit several interesting features as discussed below.

1. **Extended flow:** There is clear evidence from temperature, density, flow velocity, and kinetic pressure data that an extended 2-D flow field is produced from the narrow annular source. This is an important result in itself since it is implied in several MHD jet models[12-14] that flows originate from localized (annular and axisymmetric) regions at the accretion disk surface where field amplification or pitch angle conditions are appropriate to launch the outflow. We further observe in the experiment, that collimated, organized flow persists downstream for many source dimensions. We measure to roughly 12 gun radii downstream with no indication of the flow stream terminating or becoming less organized. So as with astro-jets, these gun-driven flows remain collimated far downstream of the source.

2. **Collimation:** The central issue in this work was to investigate plasma collimation in extended flows from the CPS-1 plasma source. As can be seen from the high density of axially distended contours in Fig. 4, there is good radial containment of the plasma flow stream. A well formed plasma channel is evident. This indicates a well collimated, almost completely axial, flow to distances far from the source (up to length to width ratio of  $> 10$ ). YSO jets are typically found with  $l/w$  ratios in the range 5-30, while much larger

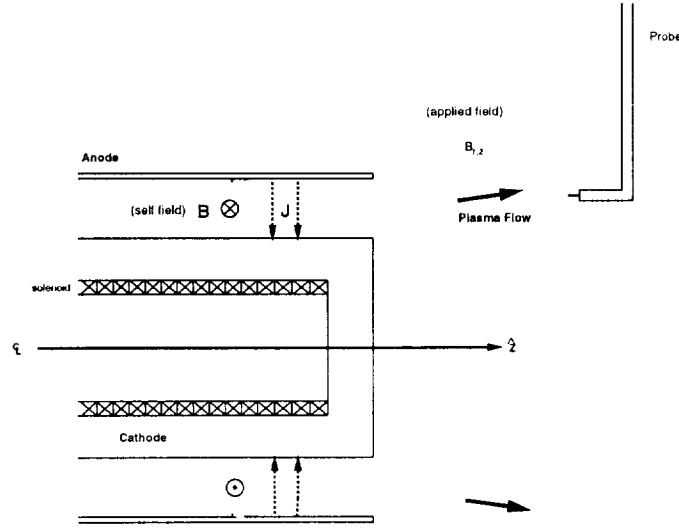


Figure 3: Schematic drawing of the MCG configuration and idealized applied field distortion in this device. Also shown is the quadrupole electrostatic probe in a typical downstream position.

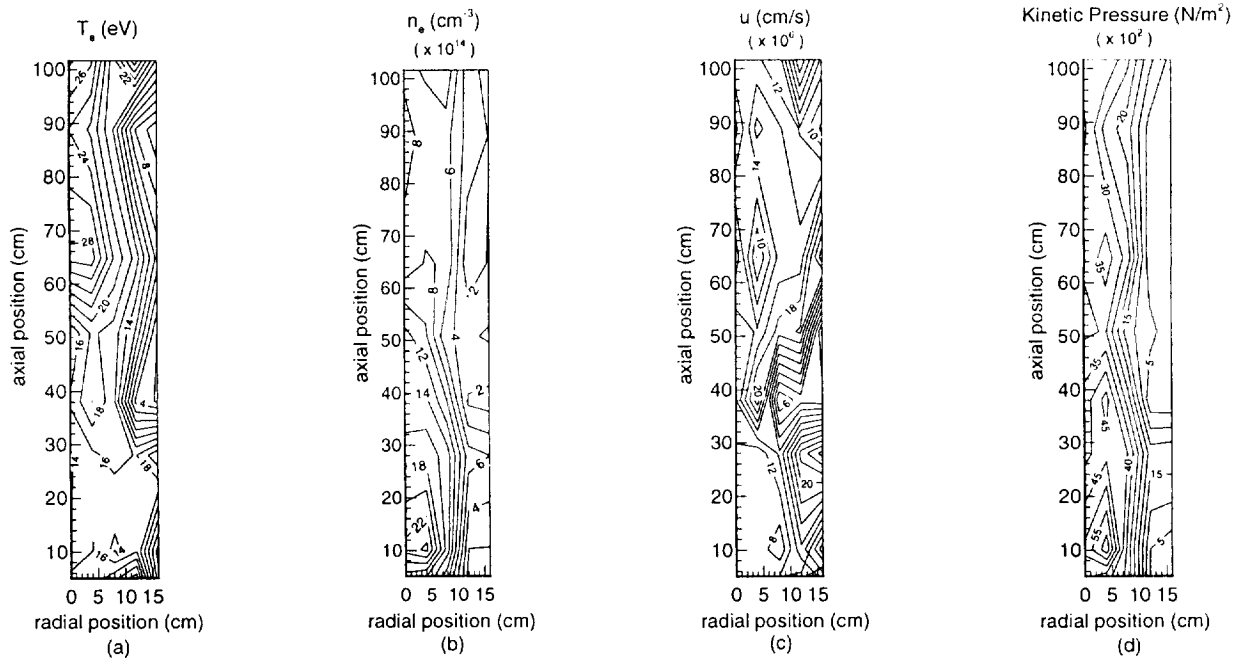


Figure 4: Contours of constant electron temperature, density, axial flow speed, and plasma kinetic pressure downstream of CPS-1 source in unmagnetized operation.

ratios are not uncommon in AGN jets. The width parameter chosen here for comparison is the collimated diameter. In the experiment the flow appears to be collimated to about the plasma source dimension, while in the astrophysical context the flow collimation radii are many times the source radii (on the order of 100 for AGN jets and perhaps  $10^4$  for YSO jets). It seems inappropriate, however, to force the scale comparison down to the astrophysical source level since we simulate only flows that have been pre-accelerated and presumably take on an initial radial dimension representative of the dynamically important MHD source (plasma gun in the experiment, disk in the astrophysical context) rather than the astrophysical point-like prime mover.

The arrangement of observed contours indicates strong radial gradients in the measured plasma parameters which include not only temperature and density independently, but plasma kinetic pressure as well. The latter suggests that radial confinement (collimation) against the outward directed kinetic pressure gradient is effective. Since the self magnetization is the only mechanism to provide such containment, this is direct indication of the effectiveness of MHD forces in collimation. This is in accord with MHD interpretations of jet collimation, suggesting that for powerful AGN and YSO flows neither radiation nor gas pressure appear to be adequate to collimate the jet momentum flux.

The data show good collimation in all parameters except for flow velocity. The lack of velocity containment is not too surprising and only indicates that the colder and lower density flow in the fringe is accelerated with the bulk flow. Since the fluid in the fringe is still reasonably high quality plasma (high  $T_e$ ), the same MHD acceleration forces may act on this fluid as well. Alternatively, the edge flow may be viscously and/or turbulently dragged by the bulk flow. Note that the data displayed in Fig. 4 are contours of constant  $v$ , not stream lines.

When external solenoid magnetization is applied the flow picture becomes more complicated. The quality of collimation is much poorer near the source and persists up to  $\sim 50$  cm from the gun muzzle. Farther downstream, however, this flow too becomes much better collimated rivalling that of the UM flow. At this axial location the applied field strength is diminished to the point where it is no longer dynamically important in guiding the flow. We conclude from these results that collimation in our case does not require an applied poloidal field and is in fact hampered by it, but does require a self (toroidal) field and, hence, plasma currents. We should guard, however, against drawing conclusions based on our preliminary findings at this point to any model that requires applied poloidal fields for collimation. In our experiment, we employ only a very specific arrangement of applied magnetization which in no way resembles that envisioned (*i.e.* perfectly axial seed field distorted to an hourglass shape as it is carried inward by radial accretion in the disk) in certain models[13]. We should reserve such judgments for future work that better replicates such field geometry.

**3. Blobs:** Clearly observed in all data sets is some large scale (but smaller than flow collimation scale) closed structure. This can be seen in Fig. 4 as a series of closed contours extending along the center line like knots in an astrophysical jet. These represent localized regions of hot plasma in the laboratory case. Such regions are also seen in the density and pressure contour maps. The initial interpretation is that these may be detached plasmoids formed from pinch forces in the MHD unstable flow stream. Though the flow is unstable to  $m = 0$  pinch, it remains remarkably well collimated. In some YSO jets that are well resolved like HH34, a sequence of variable and aperiodic knots are observed to change morphology from circular near the source to bow shaped near the leading edge[1]. An MHD detached ballistic plasmoid description is consistent with this observation as this model predicts knot flows at the jet speed and much faster than that of the working surface (to be discussed later). Alternative explanations that are popular from an astrophysical context include oblique crossing shocks as the flow attempts to expand radially, though this would imply some dynamical importance attributable to the surrounding neutral gas; or multiple bow shocks from a modulated source, though there is no signature in the experiment source function that would justify this interpretation. What's more, these knots appear to move with the jet flow. So, just as in the astro-jet case, the oblique shock model appears not to satisfy all observations since it predicts slowly moving or even stationary knots. Furthermore, were these objects a result of source modulation, one would expect softer variations both axially and radially. To be definitive, however, multiple measurements on the same plasma discharge in CPS-1 would be required in future work.

**4. Flow Speed:** The measured flow speed in the experiment is in the range 100-150 km/s. This is quite close to those observed in YSO jets. This suggests that direct comparison of some flow and interaction physics can be made, such as: importance of MHD pinch and detachment on the flow evolution time scale leading to predictions of knot size, shape, and separation; radiation and ionization phenomena by this energetic flow

interaction with stationary neutral gas cloud; flow entrainment of neutral gas; and molecular (neutral) gas flow evolution.

Further investigation on the morphology issues discussed above should include detailed experimental studies in the following areas. Some of these will require new diagnostic and/or machine hardware.

1. **Knots:** The morphology of knots as detached plasmoids or some other phenomena is not definitively demonstrated. As well, there are stability issues associated with detached plasmoids from this source that need to be investigated. The wavelength and growth rate of  $m = 0$  modes in this configuration are critical to determining the size and separation scale, as well as the dynamic evolution with respect to the bulk flow. Finer details in the flow stream should be investigated to resolve smooth changes in flow parameters across knot boundaries and distinguish this behavior from shock discontinuities. In addition, one would like to investigate self field gradients through knots to determine if hot knots require stronger self field implying that they are magnetically confined ballistic plasmoids (or conversely, are inertially confined). At the least, these investigations require multiple electrostatic and magnetic probe measurements on a single plasma discharge. To accomplish this, fabrication of several additional probes and the provision of vacuum access will be necessary. To accelerate data collection, we'll also require some automated motor drive feed-through mechanisms for positioning probes to avoid vacuum break for probe relocation. Additionally, the expansion to multiple sensors will require the addition of several wave form recorders to capture this larger data set on a single pulse. Temporal resolution is also desired in this measurement requiring signal amplification and noise reduction. The addition of a two dimensional Mach probe would also prove beneficial as a redundant axial flow measurement. As well, a 2-D poloidal flow measurement will allow mapping of the flow stream function. Finally, visible light imaging with a fast framing or CCD camera could capture 2-D flow details on a single image.

2. **Collimation and Applied Field:** Collimation should be better quantified by measuring finer details of flow parameter gradients. We need to look for divergence angle and Mach cone in the early stages of flow development both with and without external magnetization. In this way, a better description of poloidal field influence in flow dynamics and field deformation of the flow, as well as a clearer quantification of length to width ratios, will be provided. This can be accomplished with the hardware mentioned above, and the addition of some high sensitivity magnetic pickup coils so that the diminished field far downstream of the source can be accurately determined. Finally, we should strive to provide external magnetization with a two dimensional geometry more like that envisioned in theoretical MHD simulations, a radially pinched, hourglass shape. This can be accomplished by outfitting the experiment vessel with additional pulsed high field coils. Numerical simulation of the vacuum field will be performed to examine the optimal arrangement of coils. We can also easily verify the applied field strength in the experiment to answer questions regarding how large an applied field (relative to the self field) is required to dynamically influence the jet.

### 2.3. Interaction Layers

A recent experimental investigation using the CPS-1 device was performed to examine the details of MCG channel dynamics, and identify optimal thrust efficiency regions and thrust efficiency loss mechanisms for high power plasma thrusters[9]. Through the course of this work we discovered several interesting features in the magnetofluid flow dynamics that has some direct relevance to astro-plasmas. The first of these is the observation of a magnetized (and possibly collisionless) plasma shock front that entrains and “pushes” on neutral gas in the gun channel. More detail will be provided in this section on this interesting feature. In the next section, the well diagnosed phenomenon of magneto-turbulent diffusion and field deformation in flowing resistive MHD will be discussed.

During the initial startup transient of the MCG discharge, neutral fill gas is ionized within a thin ionization layer initialized near the gas injection inlet, at about mid channel. When the flow is magnetized (by external flux that links both discharge electrodes) this ionization layer is observed to slowly propagate down the flow channel to the gun muzzle. This interaction layer propagation is well described in a simple force balance model in which the self magnetic pressure behind the layer is balanced by inertial drag from the entrainment of neutral gas that is ionized as the front passes (a “snow plow” model). To demonstrate that such a straight forward model works well, we have displayed in Fig. 5 arrival time measurements for the leading edge of this narrow (approximately one channel width thick) interaction layer as a function of axial position from up



stream (negative numbers) to the muzzle (at zero). The results of the snow plow model are also displayed in this figure as a solid line, showing the agreement is excellent. Further plasma fluid modeling reveals that this magnetized interaction layer behaves as a slowly propagating magnetosonic wave, and naturally yields a layer thickness of the ion electromagnetic skin depth,  $c/\omega_{p,i}$ , which is found to be in excellent agreement with the measured layer thickness ( $\sim 2$  cm). Though the propagation of this wave is slow on the plasma magnetoacoustic scale, it is fast on the hydrodynamic acoustic time of the neutral gas propagating at about  $M = 10$  in the molecular cloud. An ordering of experimentally relevant speeds looks like; jet speed (magnetoacoustic speed in plasma)  $\sim 100$  km/s, interaction layer speed  $\sim 10$  km/s, and neutral gas sound speed  $\sim 1$  km/s.

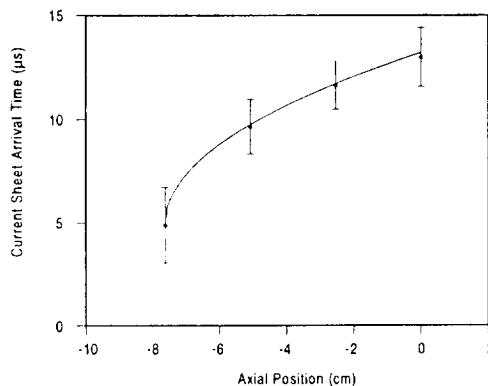


Figure 5: Arrival time of the interaction layer as a function of axial position showing good agreement with the snow plow prediction (solid line).

The interaction layer then acts as a diffuse boundary that separates the fully ionized, high temperature magnetoplasma from the cold (and probably radiative) neutral molecular cloud. In this scenario, the plasma jet acts to “push” on the molecular cloud and drive it through the channel as a normal shock. Outside the gun, it likely propagates as a bow shock, although this has not yet been experimentally verified. Since this layer acts to both accelerate the neutral gas and decelerate the plasma, a Mach disk should also be formed just behind the shock layer. This too has not as yet been experimentally observed because of the inability to measure neutral gas or plasma densities with sufficient spatial or temporal resolution. Nonetheless, this interesting observation opens some exciting astro-jet applicability issues. The first and foremost that comes to mind is the obvious similarity to a YSO jet which may well consist of a narrow well ionized plasma flow that is accelerated from disk matter in the plane of the source. This narrow and energetic jet then plows through the ambient molecular medium giving rise to visible molecular outflows and HH objects (which in this scenario represent just the brightest feature, but is usually the leading edge or terminal knot). The details of the interaction layer can now be carefully studied, as well as details of the entrainment, radiation, and ionization physics in the molecular cloud/jet interaction layer.

In support of the identification of shock features and elucidation of entrainment, ionization, a radiation physics issues mentioned above, there are several additional investigations compelled by these findings. Firstly, spectroscopic and/or fast pentode gauge measurements should be made to quantify neutral densities in the MCG channel during fill and at the leading edge of the interaction layer during the shock front propagation transient. Critical to the dynamic response of the jet/outflow system and connection to astro-jet phenomena is the relative fluid densities behind and ahead of the layer, as well as that of the ambient medium. For example, the leading edge where a YSO jet terminates (perhaps to a HH object) is a working surface that includes a strong shock since the outflow density is greater than that of the ambient medium (and greater than that of the inner jet). This is not the usual case for an AGN jet in which the rarefied jet balloons the higher density ambient medium. Density measurements will also help to quantify momentum coupling between the inner jet and molecular outflow. Collimation and general morphology of the molecular outflow could also be addressed by some of the same density and optical imaging measurements mentioned above.

Although only indirect through the collimation of the inner jet, the affect of external magnetization on outflow collimation can be addressed. Conversely, the affect of a high density ambient medium in hydrodynamically collimating the jet flow can be investigated. It is a trivial matter to subject these jet flows to a wide variety of neutral gas types and densities, for example subjecting a hydrogen plasma jet to a high density static CO<sub>2</sub> medium. We can also study the affects of mixing (viscous, ionization entrainment, turbulent or otherwise) by making spectroscopic measurements on a variety of gases. Additionally, quantification of the brightness and radiative power of the interaction layer is needed. The adiabaticity of the flow may then be discussed.

#### 2.4. Magneto-Turbulent Accretion

The fundamental physics area of investigation in our plasma sciences program is the general study of plasma flow interactions with magnetic fields. Over the past several years we have made several significant findings in this area primarily applied to MHD flows for advanced space propulsion. Among our findings are the experimental investigation and MHD modeling of anchored field line distortion by magneto-resistive MHD flows (including hall currents), and the application of such techniques in experimentally determining plasma transport and flow features. The most important of these provides for a direct magnetic field measurement of the effective electron collisionality from which micro-turbulence enhancements to collisionality can be determined[6]. We have investigated the scaling of such turbulent dissipation and have identified what we believe are saturated lower hybrid current driven modes in coaxial accelerator channels leading to flow efficiency degradation. As an example of the utility of such techniques, we show in Fig. 6 the theoretical prediction of anchored magnetic field line deformation by a flowing (left to right) magnetofluid. (The details of the theoretical model will not be included here for brevity. The details can be found in [6,8,15].) There is remarkable agreement with the experimentally measured stretched field. An example is illustrated in Fig. 7 (showing three snapshots of the field evolution at 20, 30, and 40  $\mu$ s after discharge initiation, near the peak of the input power to the CPL-1 gun). By comparing the measured distorted field with the model, we can directly determine both the magnetic Reynolds number ( $R_m = \Delta v/D$ ) from which the flow speed can be inferred, and the electron magnetization parameter ( $\Omega = \omega_{ce}/\nu_e$ ) from which we can obtain the electron collision frequency.

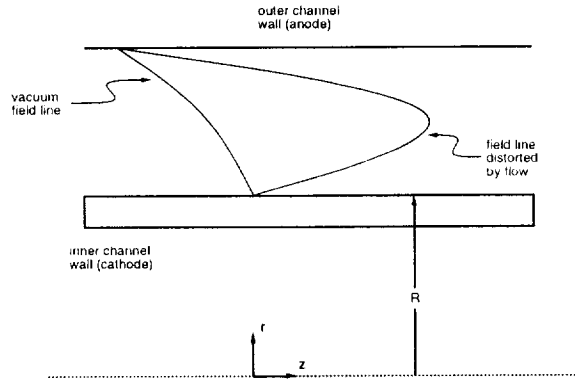


Figure 6: Theoretical prediction of anchored magnetic field deformation by left to right flowing magnetofluid.

In the experiment we find significant contribution to the electrical diffusivity ( $D = \eta/\mu_0$ ) from non-classical influences, *i.e.* plasma micro-turbulence increases the electron collisionality through wave-particle interactions and the hall effect contributes a substantial magneto-resistance. In an astrophysical context, this flow situation resembles that in an accreting plasma disk wherein initially axial magnetic flux is distorted inward to an hour glass shape external to the disk. Within the disk, the distorted field shape depends sensitively on the profile of radially inward flow as well as electron collisionality profiles. An equilibrium may well be established, as it is in the experiment, in which inward dragging of the field by the high conductivity magnetofluid is balanced by field line tension. Such a balance is critical in astro plasma disks since it

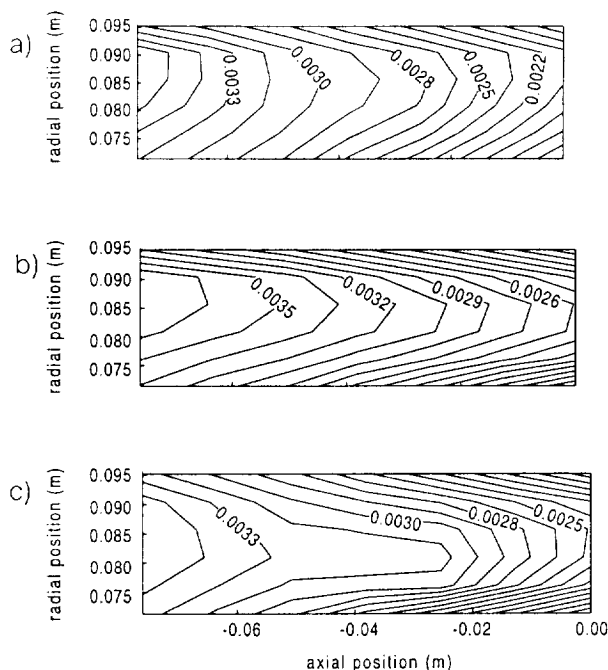


Figure 7: Measured applied magnetic flux distortion by the cross field flow.

determines accretion rates in which micro-instabilities may play an important role. It is only through fluid slippage past distorted magnetic flux that accretion is allowed, a process quite sensitive to collisionality enhancements. By establishing (in the experiment) the appropriate flow conditions to simulate the accreting magnetoplasma environment, a test bed for the study of magneto-turbulent plasma transport across the magnetic field can be developed. The following questions can be investigated: “What is the affect of micro (or fluid, ala K-II or Balbus-Hawley) turbulence on accretion in a magnetized disk? Can such experimental simulations be used to predict disk turbulence mechanisms and accretion rates?”

No additional experiment or diagnostic hardware would be required for this task. Slight modification to the existing electrostatic probe design is required to allow intrachannel plasma parameter profile measurements. Miniaturization from the current design should be sufficient. Miniature magnetic probes[16] are already available for the requisite magnetics information. Modeling capabilities will need a bit of enhancement to include radial and axial parameter profile information. A more sophisticated model should also include a self-consistent description of the external field back reaction on the flow.

## 2.5. Publications from Scoping Effort

We list below for completeness, publications that have come from our group and are either a direct consequence of this contract work or related to the topics described above.

### Direct:

*On a Laboratory MHD Plasma Flow Model of Astrophysical Jets*, R. M. Mayo, R. W. Caress, and D. C. Black, in preparation for ApJ

*Langmuir Probe Measurements of Extended Plasma Flows from a Magnetized Source and Comparison to Astrophysical Jet Morphology*, R. W. Caress, MS Thesis, NCSU, Oct. 1996.

*A Laboratory Plasma Source as an MHD Model for Astrophysical Jets*, R. M. Mayo and R. W. Caress, 24<sup>th</sup> IEEE International Conference on Plasma Science, San Diego, CA, 19-22 May, 1997.

*Experimental Investigation of a Laboratory Plasma Source as an MHD Model for Astrophysical Jets*, R. W. Caress and R. M. Mayo, Bull. Amer. Phys. Soc., **41**, 1439 (1996).

*Preliminary Investigation from a Laboratory Plasma Source as an MHD Model of Astrophysical Jets*, R. W. Caress and R. M. Mayo, Bull. Amer. Phys. Soc., **41**, 1010 (1996).

**Related:**

*Determination of Microturbulence Enhanced Electron Collisionality in Magnetized Coaxial Accelerator Channels by Direct Magnetic Field Measurement*, D. C. Black and R. M. Mayo, submitted to Phys. Plas., 1997.

*Direct Magnetic Field Measurement of Flow Dynamics in Magnetized Coaxial Accelerator Channels* by , D. C. Black, R. M. Mayo, and R. W. Caress, accepted in Phys. Plas., 1997.

*Miniature, High Sensitivity, Inductively Coupled Magnetic Probe Array for Detailed Measurements of Time Varying Magnetic Fields*, D. C. Black and R. M. Mayo, Rev. Sci. Instrum., **67**, 1508 (1996).

*Theory for a Direct Magnetic Field Measurement of Micro-Turbulence Enhanced Electron Collisionality*, R. M. Mayo, R. A. Gerwin, and D. C. Black, Phys. Plas., **2**, 337 (1995).

*A Magnetized Coaxial Source Facility for the Generation of Energetic Plasma Flows*, R. M. Mayo, M. A. Bourliam, M. E. Glover, R. W. Caress, and D. C. Black, Plasma Sources Sci. Technol., **4**, 47 (1995).

*Two Dimensional Magnetic Field Evolution Measurements and Plasma Flow Speed Estimates from the Coaxial Thruster Experiment*, D. C. Black, R. M. Mayo, R. Gerwin, K. F. Schoenberg, J. T. Scheuer, and R. P. Hoyt, Phys. Plas., **1**, 3115 (1994).

### 3. Similarity of Laboratory and Astrophysical Plasma Flow Models and MHD Applicability

Plasma Jets have been observed to emanate from a wide variety of sources on an extremely large separation of spatial scales ranging from laser produced ablating jets[17] to young stellar objects (YSO)[1,17] and active galactic nuclei (AGN) usually as extragalactic radio and visible emitting sources[1,2]. Various mechanisms have been employed in an attempt to explain the formation, acceleration, collimation, and stability of bipolar astrophysical flows. Many authors, however, favor magnetohydrodynamic (MHD) mechanisms[12,13,17] for a variety of reasons, not the least of which are the observance of strong magnetic fields in the flows, the recognized ability of the MHD pinch effect to collimate plasma, and the efficiency with which rotational energy (associated with mass accretion into a central compact object[12]) can be extracted by magnetic fields.

Existing theoretical models[12–14,17,18] well demonstrate magneto-fluid acceleration and collimation of bipolar mass outflows. These provide excellent demonstration of the ability for rotating conducting flows to generate an accelerating and collimating azimuthal field from an initial (disk threaded seed) longitudinal magnetization, thus extracting angular momentum in the rotating magnetofluid and converting it to longitudinal flow energy in what is referred to as centrifugal[13] acceleration. The presence of more realistic conditions of (a) finite electrical resistivity, (b) non-*a priori* described electrical current (or, alternatively, magnetization), and (c) the influence of Hall currents, have not been investigated. These effects have been shown to significantly influence the evolution of laboratory flows[7,8] under similar conditions, and are expected to represent important influence on the evolution and nature of the outflow (*i.e.* mass ejection). The production and acceleration of outflows originating near the prime mover is predicted[14] via MHD acceleration mechanisms involving an exclusively azimuthal field. Embedded azimuthal fields buoyed to the surface of a rotating disk, and concomitant with a poloidal current, may be responsible for Lorentz MHD axial acceleration.

The stability of these outflows with such long lived, well collimated character is not well understood. The MHD pinch force in the purely azimuthal field has an established influence on magnetic confinement

of plasma flows on dynamic (Alfvénic) time scales, but is expected to yield to violent MHD instability ( $m = 0, 1$ ) thereafter. It is observed, however, that astrophysical jets are remarkably stable on tremendous temporal and spatial scales[17]. The existence of sonic (and transonic) jets on longitudinal scales much larger than a few times their own radial dimension suggests non-ideal stabilization or, perhaps, detached plasmoid ballistic axial motion after pre-acceleration near the central object and detached by instability. These energetic flows should also be subject to a variety of micro-instabilities which subject the flow stream to small scale turbulence resulting in enhanced dissipation and drastically altered flow interaction with local magnetization.

The similarity between laboratory plasma flows in coaxial plasma devices and astrophysical jet flows can be argued pictorially. In Fig. 8 is our rendition of a bipolar plasma flow emanating from a disk threaded poloidal seed field (anchored in the highly conducting fluid) resulting in centrifugal MHD acceleration of axial plasma outflows[13,12]. Here a central massive object is the prime mover for a differentially rotating

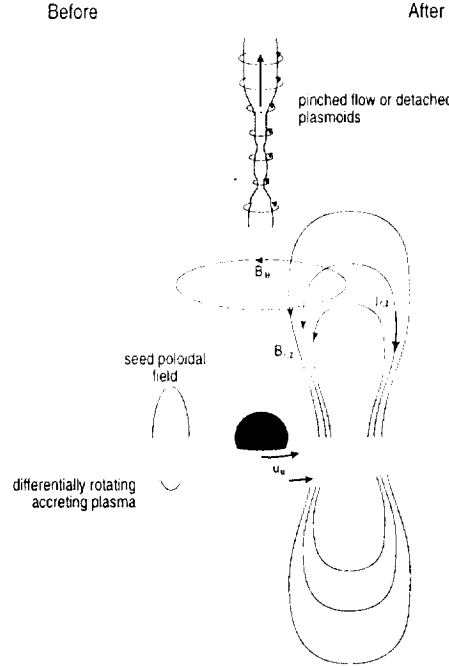


Figure 8: Pictorial demonstration of one side of a bipolar plasma flow emanating from a disk threaded poloidal seed field resulting in centrifugal MHD acceleration. The pinched stream at top is a reduced scale depiction of the flow far downstream where the field has been wound to be primarily azimuthal.

accreting plasma. The differential rotation distorts the seed poloidal magnetization, generating an azimuthal field, which in turn provides the acceleration with the induced poloidal current,  $j_{r,z}$ . The pinched stream at top is a reduced scale depiction of the flow far downstream where the field has been wound to be primarily azimuthal. The flow is collimated here by the azimuthal field, and may be stabilized by poloidal field stretched from the seed field.

Very near the prime mover poloidal fields of any significance are destined to be quickly destroyed under the tremendous tension of rotation and the likely turbulent flow in this region. Here, however, purely toroidal ( $B_\theta$ ) fields may exist and are amplified by differential rotation[14]. These may protrude through the surface via magnetic buoyancy. Current attachment to the disk allows a net Lorentz MHD force ( $j_r \times B_\theta$ ) in each pole, resulting in bipolar acceleration and MHD flow (mass ejection). In this scenario the axial flow is again constricted by the azimuthal field, but this time without stabilization from poloidal magnetization. As this flow becomes kink unstable, detachment into discrete plasmoids may be expected. Given sufficient initial

acceleration, however, these plasmoids may traverse substantial distances before dispersing into cocoon, resulting in a rather narrow divergence.

This picture should be compared to that produced in a Magnetized Coaxial Plasma Gun (MCG) device like CPS-1 as shown in Fig. 3. The flow is depicted here as a fully developed axial (to the right) plasma stream, the development of which follows the energizing of the experimental apparatus via a capacitive energy storage unit. The field lines are distorted by the flowing magnetofluid from those produced in a DC solenoid coil located within the plasma gun. This device produces flows which have magnetic field topological similarity to the astrophysical jets depicted in Fig. 8. The poloidal field lines are distorted down stream by the flowing magnetofluid in both the experiment and astrophysical cases with anchor points at or very near the plane of origin for the axial flow. In the case of the experiment these footpoints are in the gun electrodes, whereas they are in the accretion disk in the former. Both flows possess toroidal (azimuthal) field which serves to accelerate the flow near the source and constrict the flow at large distances from the source. The laboratory experiment, CPS-1, may also be operated in an unmagnetized fashion (absent the poloidal field) so as to simulate the purely MHD acceleration scheme in the exclusively azimuthal field, as described earlier for astrophysical flows originating near the central object.

While the field topologies are similar, the flow field likeness is equally intriguing. Plasma flow streams driven in the experimental device are well collimated, transonic, near ideal (low electrical resistivity) MHD, magnetized plasma flows. This scenario is much like what is expected in astrophysical flows[2]. While the absolute magnitude of flow speeds and energies are quite dissimilar (except in the case of a YSO jet which exhibits quite comparable flow speeds to the experiment), it is the plasma dynamic and flow regimes that determine the underlying physical processes driving the event. It is this likeness that provides the basis for applicability of the laboratory experiment to protostellar or extragalactic jet observations.

Direct parameter scaling arguments are difficult in connecting these spatially and temporally diverse objects. This is rationalized somewhat by the paucity of quantitative information from astronomical observations. Yet, there exists enough quantitative data to make a strong case of applicability in plasmadynamic regime[2]. Many examples of magnetic field observations in astrophysical jets suggest that electromagnetic forces are dominant over gravitational and kinetic pressure. This is certainly true of the laboratory experiment wherein gravitational effects are completely ignorable and the importance of kinetic pressure, gauged by the plasma  $\beta \ll 1$  ( $\beta = 2\mu_0 p/B^2$ ), is readily neglected. Further, gyro and Debye scalings are such that both laboratory and astrophysical flows may be classified as MHD. The Debye length (electrostatic skin depth) in both cases is much smaller than any characteristic length scale by  $\sim 10^{-8}$  to  $10^{-5}$ . As well the gyro scale length (radius of the Larmor orbit, which is approximately the electromagnetic skin depth), is also much smaller than spatial scales by  $\sim 10^{-5}$  to  $10^{-2}$  in both flows. These crude arguments give credence to our acceptance of the applicability of an MHD plasma model to these phenomena.

### 3.1. Extended Effort

The applicability of existing laboratory plasmas facilities to the study of stellar and extragalactic plasmas should be exploited to elucidate underlying physical mechanisms that cannot be ascertained through astrophysical observation, and provide baseline to a wide variety of proposed models, MHD and otherwise. The work proposed herein represents a continued effort on a novel approach in relating laboratory experiments to astrophysical jet observation. There exists overwhelming similarity among these flows that has already produced some fascinating results and is expected to continue a high pay off in further flow similarity studies.

The main expected results can be summarized as follows:

1. Suitability of laboratory sources for simulating astrophysical MHD phenomena.
2. Description of mass ejection, morphology, and collimation and stability of energetic outflows.
3. Description of the effects of external magnetization on collimation and stability of such outflows.
4. Description of the interaction of such flows with background neutral gas, the generation of visible emission in such interaction, and the effect of neutral clouds on jet flow dynamics.
5. Quantification and scaling of cross magnetic field transport in turbulent accretion-like flows.

6. Critical test of MHD models for astrophysical jets.
7. Development of miniature 2 (or 3)-D electrostatic flow probe.

## REFERENCES

- [1] BURGARELLA, D., LIVIO, M., and O'DEA, C., editors, *Astrophysical Jets*, Cambridge University Press, Cambridge, 1993.
- [2] BEGELMAN, M. C., BLANFORD, R. D., and REES, M. J., *Rev. Mod. Phys.* **56** (1984) 255.
- [3] KUNDT, W., editor, *Astrophysical Jets and Their Engines*, D. Reidel Publishing Co., Dordrecht, Holland, 1987.
- [4] MAYO, R. M., BOURHAM, M. A., GLOVER, M. E., CARESS, R. W., EARNHART, J. R. D., and BLACK, D. C., *Plasma Sources Sci. and Technol.* **4** (1995) 47.
- [5] SCHEUER, J. T., SCHOENBERG, K. F., GERWIN, R. A., HOYT, R. P., HENINS, I., BLACK, D. C., MAYO, R. M., and MOSES, R. W., *IEEE Trans. Plas. Sci.* **22** (1994) 1015.
- [6] MAYO, R. M., GERWIN, R. A., and BLACK, D. C., *Phys. Plas.* **2** (1995) 337.
- [7] SCHOENBERG, K. F., GERWIN, R. A., HENINS, I., MAYO, R. M., SCHEUER, J. T., and WURDEN, G., *IEEE Trans. Plas. Sci.* **21** (1993) 625.
- [8] BLACK, D. C., MAYO, R. M., GERWIN, R. A., SCHOENBERG, K. F., SCHEUER, J. T., HOYT, R. P., and HENINS, I., *Phys. Plas.* **1** (1994) 3115.
- [9] BLACK, D. C., MAYO, R. M., and CARESS, R. W., Direct magnetic field measurement of flow dynamics in magnetized coaxial accelerator channels, accepted in *Phys. Plasmas*, 1997.
- [10] GLOVER, M. E., MAYO, R. M., and BOURHAM, M. A., Quadruple langmuir probe measurement of plasma parameters and flow velocity in the CPS-1 magnetized coaxial plasma gun facility, in *Bull. Am. Phys. Soc.*, page 1967, American Physical Society Division of Plasma Physics, 1993, Volume 38, (St. Louis Conference).
- [11] BURTON, R. L., DELMEDICO, S. G., and ANDREWS, J. C., *J. Prop. and Power* **9** (1993) 771.
- [12] CONTOPOULOS, J. and LOVELACE, R. V. E., *Astrophys. J.* **429** (1994) 139.
- [13] BLANDFORD, R. D. and PAYNE, D. G., *Mon. Not. R. Astr. Soc.* **199** (1982) 883.
- [14] CONTOPOULOS, J., *Astrophys. J.* **450** (1995) 616.
- [15] BLACK, D. C., MAYO, R. M., and CARESS, R. W., Determination of microturbulence enhanced electron collisionality in magnetized coaxial accelerator channels by direct magnetic field measurement, submitted to *Phys. Plasmas*, 1997.
- [16] BLACK, D. C. and MAYO, R. M., *Rev. Sci. Instrum.* **67** (1996) 1508.
- [17] BELL, A. R., *Phys. Plasmas* **1** (1994) 1643.
- [18] SHIBATA, K. and UCHIDA, Y., *Publ. Astron. Soc. Japan* **37** (1985) 31.