# Topic: Jets/Outflows and Impact on Cosmic Structures

## 1.1 Introduction and Current Status

Fast, axially collimated outflows, or 'jets', are ubiquitous in astrophysics. They flow from most classes of compact objects that spin and/or accrete matter from their surroundings, which range from young stellar objects (YSOs, see Fig.1), neutron stars, and stellar mass black holes (BH) to super massive black holes (SMBH) in the centers of galaxies (see Fig. 2). Compactness leads to high gravitational potential. Rapid spin provides a second free energy source. The axial symmetry of spin allows energy, momentum, and angular momentum to concentrate and be transported away along the symmetry axis, typically in oppositely directed jet pairs. Some jets are probably matter dominated (highly ionized plasmas) while others may consist primarily of electromagnetic energy, and some a blend (electron-positron pairs are involved in some high energy settings). The jet speed can range from a few tens km/sec to close to the speed of light. The total jet energy can be a large fraction of the gravitational energy released during the host objects formation (up to a fraction of their rest mass energy), and/or can be sufficient to 'de-spin' the host compact object.

We also now realize that jets play an important feedback role in the evolution of their host systems. Jets from protostars energize the parent, star-forming molecular cloud, possibly regulating the rate and efficiency of star formation. There is ample evidence that jets from SMBHs in galactic nuclei both energize the nearby interstellar plasma and, for those in galaxy clusters, impact the intracluster medium (ICM) and the inter-galactic medium (IGM), contributing to the extra-galactic magnetic fields and cosmic rays, including ultra-high energy cosmic rays (UHECRs), neutrinos, and gamma rays. Jets and lobes serve as a useful calorimeter of the non-thermal energy component in the overall cosmic energy flow.

Many fundamental challenges remain for the understanding of jets and outflows. To name a few: 1) Plasma conditions of jets are not well known. What are jets made of? More and better measurements are needed around the jet "engine", in the jets, and at the jet termination. 2) The range of scales is vast: As an example, the jet originates from a SMBH at ~ 1 AU ($10^{13}$ cm) scale but extends to mega-parsecs ($10^{24}$ cm). There are even smaller scales associated with the collisionless nature of jet plasmas. This vast scale separation makes building a coherent theory from engine to termination extremely challenging. 3) Lack of plasma physics understanding. Plasma physics processes govern the energy transfer among gravitational, kinetic, thermal, magnetic/electric components and particles. How are jets accelerated and collimated? How do magnetic fields behave? Why are jets stable? How does large-scale fluid motion "communicate" with small-scale kinetic processes? Will relativistic effects change the physics drastically? What are the dissipation processes to produce 10 TeV electrons and $10^{20}$ eV cosmic rays? etc.

Jets/outflows therefore present a suite of important laboratories to test our understanding of plasma physics. Such knowledge conversely provides part of the necessary physics underpinning for understanding the dynamics and evolution of the Universe. Thus, astrophysical jets/outflows offer a natural laboratory for a concerted study by the astrophysics and plasma communities. Substantial progress can only be made when these two communities work together and when observation, laboratory experiments, theory and simulation communities have built strong ties, and the infrastructure (for research collaboration and funding) is conducive for such efforts.

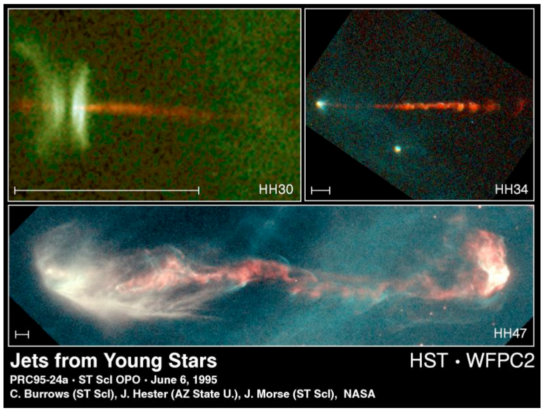

*Fig 1: Three examples of YSO jets on different scales. In each case, the scale bar corresponds to a length scale of 1000 AU, and the image is oriented so that the jet source is on the left. The compact source is obscured from direct view in each case, but its light is scattered from the walls of the outflow cavities (white light). For HH30, there is an obvious disk surrounding the central object, seen edge on.*

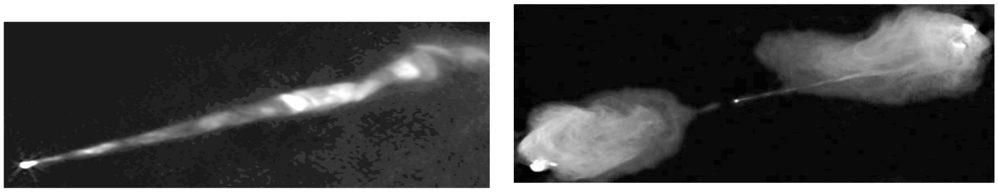

*Fig 2: The left image (Cyg A), 40 kpc scale, shows 2 jets which have NOT gone unstable or ever seriously disrupted. The right image (M87), 2 kpc scale, shows a jet which is beginning to be seriously disrupted, by a growing helical instability.*

### 1.2 Key Scientific Challenges

A) Challenge I: Physics of jet launch and acceleration

Due to the difficulty of direct observations of the disks and central objects (young stellar objects, neutron stars and black holes), it is challenging to constrain the initial condition for jet production. For YSOs, we need improved measurements of magnetic field strengths and orientations on all scales, especially the launching regions. The Atacama Large Millimeter Array (ALMA) may be able to measure B fields on ~1AU scales in the nearest sources. High spectral resolution spectroscopy, combined with high spatial resolution, allows us to probe the physical properties of outflowing material (e.g., bulk velocity, density, temperature, shock velocity, ionization state). Measurements of jet rotation are also important for determining the launching region and mechanism. For extragalactic sources, the VLBI arrays are beginning to probe close to the central BH accretion disk “engine” where the jets are launched. Recent VLBI results reveal time-varying helical magnetic structures that characterize the jet-launching region on scales as small as one light year. Magnetic field strengths and plasma densities are such that Faraday rotation effects are readily seen at these compact dimensions, so that quasi-3D imaging of the jet launching regime can be undertaken. This will be important in addressing questions such as whether jets carry significant currents, as well as the jet power in different components (kinetic vs. Poynting).

It has become possible during the past decade to perform General Relativistic MHD simulations of disks around a BH while investigating the launching of relativistic jets. Many questions, however, remain: If the jets are magnetically mediated, where do the large-scale fields come from? What controls the advection, diffusion, and/or dynamo of B field in magneto-rotational instability (MRI) disks ($\beta>1$) and the non-MRI disk corona ($\beta<1$, where $\beta$ is thermal pressure over magnetic pressure)? During the jet launching, is the acceleration primarily by magneto-centrifugal effects, by ``magnetic pressure" effects, or by non-magnetic forces? What determines the mass loading and thermal energy input at the outflow base? Under what conditions do magnetically dominated jets occur rather than hydromagnetic jets? What do jets consist of, electrons/ions or $e^{\pm}$ pairs? What determines the bulk Lorentz factors and energy fluxes of jets? And how do these quantities depend on the BH spin, the disk magnetic field, and the accretion rate? What is the role of the angular momentum outflow of jets and winds? The plasma physics understanding (including relativistic MHD) in these questions is clearly needed in order to make progress.

Substantial progress has also been made during the past decade using laboratory plasma experiments to model some aspects of the physics of astrophysical jets. If the dynamical scaling constraints are properly applied, one can reproduce astrophysical processes on some segment of their time-evolution. Many of the astrophysical systems are well described by ideal magnetohydrodynamics, due to very large values of Reynolds ($LV/\nu$), magnetic Reynolds ($LV/\eta$) and Peclet numbers ($LV/\alpha$, where $\nu$, $\eta$, $\alpha$ are viscosity, resistivity, and thermal conductivity, respectively) - primarily because of the very large spatial scales involved. Recently it has become possible to include dynamically significant magnetic fields and to achieve sufficiently high magnetic Reynolds numbers and high Alfvénic Mach numbers in some laboratory jet experiments. Some questions under investigation include: How does the Lorentz force convert electrical power into directed flows? Where and how does the jet acceleration take place? What is the quantitative scaling showing how different combinations of electrical and material inputs (voltage, current, field topology, mass source morphology) produce different types of flows (e.g., low mass density with high velocity, high mass density with low velocity, degree of collimation)?

### B) Challenge II: Physics of jet collimation, propagation and termination

For YSOs, launching happens on scales from ~1 stellar radius to ~1AU, while collimation appears to occur on size scales of ~100AU. It is unknown whether collimation is primarily due to the internal outflow properties or to an interaction with the environment. Time series of images and spectra, spaced a few to several years apart, allow us to probe the interaction of outflows with their environments, as well as internal outflow-outflow interactions. These studies are useful for determining whether the clumpiness/variability observed in jets is due primarily to variations in jet launching source, instabilities in the flow, or interactions with environment. This will also put constraints on the amount of feedback from forming stars on the parent molecular cloud. For extragalactic sources, imaging polarimetry with VLA already shows evidence for helical magnetic field structures on kpc scales. The tentative measurement of a jet current is ~$10^{18}$ amperes, and the spatially averaged plasma $\beta$ could be as low as $10^{-5}$ at currently available resolutions. In the intracluster medium (ICM), X-ray observations of jet-blown cavities have allowed the first direct measures of the energy deposition by BH-driven jets. Radio observations (e.g., VLA and Expanded VLA) of the morphology of jets/lobes provide valuable constraints on the composition of jets and the physics of jet/ICM interaction. They, in turn, provide unique probes into the physical and dynamical properties of the ICM.

Some fundamental questions regarding jet collimation, propagation, and termination still remain. Are jets collimated by the magnetic hoop force, pressure of external medium, or by un-collimated outer disk winds? What are the key parameters of the jets that control the global stability of the jet to kink and other instabilities? How will the current-driven kink instability change in relativistic MHD? What processes will govern the energy conversion from B-field dominated limit to kinetic energy? What is (are) the mechanism(s) for *efficiently* accelerating leptons *in situ* to energies sufficient to give TeV radiation (shock acceleration, reconnection, KH instability, ..)? Do UHECRs come from BH/disk/jet/lobe systems? How important are the jets for energy/momentum feedback into the ISM and for driving turbulence in molecular clouds? How will AGN jets excite turbulence in the ICM and IGM? Will AGN provide significant magnetic fields and cosmic rays to the ICM and IGM? What are the quantitative feedback effects of SMBH jets on the cosmic structure formation?

Existing laboratory experiments can produce highly collimated jets that become kink unstable at a critical length and in certain cases manifest internal shocks, knots, and even disconnection of the jet from the source. Existing experiments can thus be used in the near term to address a set of questions discussed above, including: What collimates the jets? What is the jet stability with sufficiently strong axial currents (magnetic fields)? What mechanisms can suppress the kink instability in jets? How does the jet interact with the ambient medium? Is there intrinsic connection between the physics of radio jets/lobes and laboratory spheromak and reversed field pinch experiments?

### 1.3 Major Opportunities:

I) Establishing new infrastructure for jet research

The study of astrophysical jets is a very active research area in Astronomy and Astrophysics and it is ripe for progress with significant inputs from plasma physics. Nearly all current major observatories (Fermi, Chandra, Spitzer, Pierre Auger, HST, VLT, EVLA, VLBA/VLBI, etc.) contribute strongly to understanding the nature of jets. It has been well established that jets play an important role in determining the physical condition of the interstellar medium (ISM), the intra-cluster medium (ICM), and the inter-galactic medium (IGM). Furthermore, they could be closely related to the origin of Ultra-high energy cosmic rays (UHECRs). The last decade also saw major advances in two fronts: the use of laboratory experiments to study jets and sophisticated multi-dimensional general relativistic MHD simulations of jets. Yet, we do not yet have an intellectual grasp on these systems. An understanding from the plasma physics point of view of jets is urgently needed. Presently, the jet research is fragmented (relatively little collaboration among observers, experimentalists, theoreticians and people doing simulations). Different funding agencies, while supporting jet research in certain ways, have different priorities and constraints.

We propose the formation of a consortium on Astrophysical Jets, with funding for research and regular workshops, bringing together interested astronomers and plasma scientists, and taking advantages of recent breakthroughs in parallel numerical simulations and laboratory experiments. Such a consortium needs to be supported by multiple agencies (DOE/OFES, NSF and NASA). We especially encourage direct contact between members of the different communities, via in-person visits or attendance at small meetings; this encourages the growth of new ideas and intuition much more efficiently than via the traditional transfer of information via journals and large conferences. Specific suggestions include: 1) seeking funding for development of research networks, such as the very successful JetSet network created in the EU; 2) having members of the computational or observational communities make extended visits to experimental facilities and collaborate in the operation and interpretation of experiments; 3) encouraging collaboration and cooperation between the plasma community and the radio astronomy community (so to fully utilize available resources on observations of magnetic fields and jets); 4) holding focused workshops on specific topics (such as why jets are stable), summer/winter schools, and joint seminars, etc.

## II) Opportunities from radio astronomy

Emerging new capabilities of radio astronomical instruments have the potential to play a pivotal role in revealing the plasma processes in extragalactic AGN jets. The jet-launching region near a galaxy's SMBH is accessible to VLBI and on the kiloparsec-to-megaparsec scale phase of SMBH-powered jets. The critical need is to have cross-jet angular resolution. This requires imaging interferometers spanning a few hundred km, with full polarization capability at wavelengths up to ~ 30cm. For probing the launching region, logistics and additional equipment, particularly short wavelength receivers, are needed to reach as close as possible to the SMBH accretion disk zone. For the required sensitivity in future VLBI imaging, the exceptional size of the Arecibo telescope and the Green Bank Telescope are key existing US resources. For Kpc-Mpc scales, the imaging capability of the new NRAO EVLA is well developed in the needed direction, except for its limited maximum baseline of 35 km. To resolve the jets transversely at cm wavelengths requires a 10 to 30 times larger maximum baseline. A design and proposal have been produced for such an instrument, the "EVLA2", but this appears to be no longer active. In the absence of a future US-based EVLA2, a European array of similar dimensions might conceivably be combined with the 35 km EVLA to achieve similar capabilities.

## III) Understanding why jets are stable over long distances

One of the most challenging aspects of understanding jets is why they are stable over long distances (the extent of the jets can be > $10^{10}$ times of the size of engine). Since the stability is closely tied with the global jet dynamics, this is one parameter space where observations (having enough resolution), experiments, and theory/simulations can address jointly. The challenges include better constraints on the jet composition on large scales and well-developed theory incorporating more detailed measurements and observations. We believe that through a close collaboration among observation, experiment and theory/simulation, significant progress can be made in this area, including modeling the jet energetics, stability and morphologies in well characterized background environments (e.g., radio jets and lobes in galaxy clusters).

## 1.4 Impacts and Major Outcomes

Jets/outflows can be very high β (e.g., the ICM or IGM, and possibly BH-driven jets far from their origin). Alternatively, they can be very low β (e.g., BH-driven jets near their origin). Jet/outflow systems often involve high-speed flows. Examples are relativistic flows in jets and pulsar winds; supersonic or super-Alfvénic flows in jets; supersonic or super-Alfvénic turbulence in the ICM and IGM. The astrophysical and laboratory plasma communities need to work together more closely for mutual benefit, in order to understand which plasma processes are important, and how they operate in different parameter spaces. It is known that jets from YSOs and from SMBHs play significant roles in regulating their surroundings. Consequently jets impact our understanding of processes such as star formation, galaxy formation, physics of the ICM and IGM, all problems of paramount importance in astrophysics.

## 1.5 Connections to Other Topics

The study of jets naturally brings together a number of topics discussed in this Report. For example, the existence and critical role of magnetic fields in disks around stars and BHs and in facilitating jet launching are closely related to the Dynamo and Angular Momentum Transport processes. The production of high-energy particles (perhaps UHECRs) and photons (observed up to 10 TeV) is determined by Particle Acceleration processes such as Collisionless Shocks and Reconnection. The relativistic speeds observed in jets and the inferred high magnetization call for studies of Relativistic Plasmas in extreme parameters. Jets powered by accretion into SMBHs, some of the most prodigiously luminous radiators in the Universe where Radiation Hydrodynamics play an essential role. Accretion disks and jets/lobes are believed to be inherently turbulent. Turbulence could strongly influence the accretion process and energy conversion from magnetic fields to particles. On large scales, jet propagation and stability begs for understanding of Shear Instability.