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Hydrodynamic and Hydromagnetic Stability of Black Holes with Radiative Transfer

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Abstract. Subrahmanyan Chandrasekhar (Chandra) was just eight years old when the first astrophysical jet was discovered in M87. Since then, jets have been uncovered with a wide variety of sources including accretion disks orbiting stellar and massive black holes, neutron stars, isolated pulsars, γ-ray bursts, protostars and planetary nebulae. This talk will be primarily concerned with collimated hydromagnetic outflows associated with spinning, massive black holes in active galactic nuclei. Jets exhibit physical processes central to three of the major research themes in Chandrasekhar's research career - radiative transfer, magnetohydrodynamics and black holes. Relativistic jets can be thought of as "exhausts" from both the hole and its orbiting accretion disk, carrying away the energy liberated by the rotating spacetime and the accreting gas that is not radiated. However, no aspect of jet formation, propagation and radiation can be regarded as understood in detail. The combination of new γ-ray, radio and optical observations together with impressive advances in numerical simulation make this a good time to settle some long-standing debates.

Keywords. Active Galactic Nuclei, Black Holes, Jets

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1. Introduction

Considerable advances have been made, both observationally and theoretically, towards understanding Active Galactic Nuclei (AGN) which are now known to be associated with massive black holes. As the mass of the black hole is $\sim 100 - 1000$ times the binding energy of the associated galaxy, liberating even a small fraction of the accretion energy over the lifetime of the active nucleus may have a significant impact on the host galaxy and its surroundings. We now have a much better understanding of the demography of AGN, and there is widespread acknowledgement that AGN have an important role in galaxy formation and evolution [13]. This is real progress.

Relativistic outflow in the form of jets [8, 11] is a common accompaniment to black hole activity. However, despite much effort, we do not have a widely accepted description of jet structure and composition, we are still unsure about the particle acceleration and

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emission mechanisms, and we still cannot interpret AGN taxonomy in physical terms. Fortunately, we are learning much more about jets and their context from γ-ray observations. These include statistical and individual studies of blazars - relativistic jets that are directed towards us - by Fermi Gamma-ray Space Telescope and studies of nearly a hundred nearby sources by Atmospheric Cerenkov Telescopes like H.E.S.S. and VERITAS. In addition VLBI techniques are being pushed to shorter wavelengths, improving the angular resolution and more ambitious radio monitoring campaigns are underway. There has also been a renaissance of optical polarimetry in response to some encouraging results. Each of these developments augurs well for the future.

2. Ten Challenges

It is worth recalling some of the questions where consensus has not yet been reached, but where progress is imminent. We will briefly summarize the issues but can only give a few representative references to the literature.

1. *Locate the Sites of Emission*. There should be no controversy when it comes to locating the radio emission. It seems to be generally true that unresolved radio cores are self-absorbed and the features that are seen to move superluminally are optically thin regions of enhanced emission that lie beyond the core [19]. If the jet spectral flux is S Jy at a wavelength of λ, the observed jet brightness temperature is $10^{12}T_{12}$ K, and $0.1\theta_{-1}$ radians is the angle the jet makes to the line of sight, while the angular diameter distance is D_9 Gpc, then the radius of core emission is

$$r_{\rm core} \sim (S/T_{12})^{1/2}(\lambda/1{\rm cm})D_9\theta_{-1}^{-1}{\rm pc}$$

   The brightness temperature is related to the energy of the emitting particles and this will be many thousands of black hole gravitational radii ($m \sim 1.5\times10^{14}(M/10^9{\rm M}_\odot){\rm cm} \sim 5000(M/10^9{\rm M}_\odot)s$) at cm wavelength, increasing roughly in proportion to the wavelength. Radio jets have been traced down to a few hundred gravitational radii in the case of M87, which has a large measured mass of roughly six billion solar masses. Unfortunately the cores are just too small to resolve with terrestrial baselines.

   A recent controversy involves locating the origin of the γ-ray emission. The minimum radius from which γ-rays of energy E_γ GeV can emerge is the "gammasphere" where the source becomes opaque to pair production on soft photons of energy $\sim 500(1{\rm GeV}/E_\gamma)$ eV[10]. This radius, r_γ, is hard to estimate because we do not know what fraction of the soft photons will be scattered into the path of the jet. A reasonable guess is that r_γ is a hundred gravitational radii when $E_\gamma \sim 1$ GeV, increasing roughly proportional to the γ-ray energy [3]. If the γ-ray emission comes from r_γ, the higher energy photons should vary slower and later than the lower energy photons. So far, this effect is not really observed. Alternatively the γ-ray emission may originate at much larger radii where pair production opacity is not an issue [12]. In this case, a disturbance, such as a shock, instigates a burst of particle acceleration which may be either stationary or convected outward with the flow [27].

   The challenge is that very rapid variations are observed. Timescales $t_{\rm var}$ less than an hour, and even as short as a few minutes have been reported at TeV energy indicating upper limits $r < 10^{16}(\Gamma/10)^2(t_{\rm var}/1{\rm hr})$ cm where Γ measures the jet bulk Lorentz factor. Typically the most stringent upper limits on the emission radius, not applicable to most sources, are thousands of gravitational radii. (In the case of the Fermi telescope, photon statistics preclude measuring a variation timescale much shorter than a day at $\sim$GeV energies.) Note also that variations on timescales shorter than m are very difficult to orchestrate in any model.

This avenue of research is being transformed by large scale monitoring campaigns like that at Owens Valley Radio Observatory which is starting to enable statistical studies of controlled blazar samples [26]. More than a thousand sources are being tracked at 15 GHz roughly twice weekly. Already it has been shown that γ-ray-loud sources are more radio variable on average than their γ-ray-quiet counterparts and that lower redshift sources may also be more variable. More radio correlations are expected to emerge with time, and searches for optical-γ-ray lags are also promising.

2. *Map Jet Velocity Fields*. The simplest, and still most common, jet model comprises a single homogeneous spherical source moving with uniform velocity! Progressively more sophisticated variants impose a jet geometry on a uniform flow, introduce a "spine-sheath" shear flow and allow for acceleration or deceleration (e.g., Laing & Bridle 21). (A typical jet flow is expected to be accelerated by gas and magnetic pressure gradient initially and then decelerated as it entrains gas from its surroundings.) Even if these prescriptions provide adequate representations of the large scale velocity field, most particle acceleration schemes invoke smaller scale irregularities such as instabilities, wave modes, shock fronts and fluid turbulence.

   Most sources exhibit more varied and complex variability than most models. This may be because Doppler boosting is a very dramatic amplifier and we select insignificant parts of a jet that happen to maximize the Lorentz factor while including us within the emission cone with opening angle $\sim \Gamma^{-1}$. Shocks introduce further kinematic complications as the speed of the emitting material, which dictates the amount of Doppler boosting, necessarily differs from the speed of the feature itself. Similar considerations apply to shear flow instabilities.

   Perhaps the best way to get more observational insight into jet velocity fields may be to carry out more mm and even sub mm VLBI with $\sim$10,000 km baselines to probe those regions that are opaque to and unresolved by radio VLBI. It will be especially interesting to see if the flow is accelerating within $\sim 100m$.

3. *Affirm Synchrotron and Compton Emission*. The total electromagnetic spectrum from a blazar has a "Bactrian" form with the lower, synchrotron hump extending from $\lesssim 100$ MHz to UV/X-ray energies and the upper, Compton hump extending to γ-ray energies [17]. The photon energies associated with the maxima of the two humps appear to decrease with increasing overall power.

   Despite this simplicity, alternative emission processes are still being explored. The lingering problems associated with intra-day variability, which may not all be attributable to refractive, interstellar scintillation, have triggered a resurgence of interest in coherent, most reasonably cyclotron maser - emission, given its operation in far less stimulating environments within the heliosphere. There is still the constraint that the emergent radiation must avoid nonlinear absorption along the line of sight. Simultaneous radio polarimetry (including circular) at many frequencies may be the best way to settle this matter.

   Another complication is the possibility that the radio-emitting region of the jet is inhomogeneous[22]. We have already suggested a radius to frequency mapping which would imply that core radio emission observed with wavelength $\sim 1\text{mm} \lesssim \lambda \lesssim 1\text{m}$ extends over a range of roughly a thousand in radius and, if so, the relationship between the variation at different frequencies should help us to decide if the excitation is local at each radius or due to a travelling disturbance. One intriguing possibility is that the synchrotron emission that forms the first, lower frequency, hump is the superposition of power law spectra with the highest and lowest frequency emission coming from large radius varying together and following the intermediate frequency emission near the peak of the hump coming from smaller radius. Associated Compton variability patterns might also be expected. Alternatively, if the emission is dominated by a single zone the whole spectrum would be expected to vary together. It still does not seem possible to decide this observationally. However, extensive, multi-frequency monitoring campaigns, instigated by the Fermi observations, should help considerably.

There is less confidence that we understand the nature of the soft photons that are Compton scattered. They could be "internal" synchrotron photons produced within the jet. Alternatively, they could be "external" photons perhaps originating from the accretion disk and scattered into the path of the jet by thermal electrons outside the jet. There is evidence that the photons are internal in low power sources like BL Lac objects, whereas external photons are more important for the high power quasars. However, the answer may also depend upon the energy of the inverse Compton-scattered photons.

A much discussed alternative for the γ-ray emission is that it is hadronic, due to the creation of pions in proton collisions. Indeed this was a motivation for the construction of underground very high energy neutrino detectors like IceCube [4]. Furthermore, relativistic jets are one of the few conceivable sites where Ultra High Energy Cosmic Rays could be accelerated to energies ~ 1 ZeV. So far no neutrino sources have been found; neither have there been convincing identifications of radio sources with UHE cosmic ray arrival directions [2]. In addition there is no sign of pion "bumps" which might be present in some models. There are other problems including the difficulty in placing the hadronic jets into a plausible dynamical context, which does not invoke unreasonable powers. Overall, though it is easier to imagine seeing signs of hadronic jets than conclusively ruling them out on grounds other than plausibility.

4. *Determine the Jet Composition*. In general, there are three contributors to relativistic jet momentum - protons, leptons and electromagnetic field. It is quite reasonable that there are transformations from one form to another as the jet expands and that the dominant contribution at a given radius changes from jet to jet. The one conclusion of which we can be certain is that jets are not purely leptonic close their origin as the radiative drag due to Compton scattering would be far too large. The choice for the momentum carrier is between electromagnetic field and protons. The former is the more attractive idea because it makes a more direct connection to the particle acceleration that must ultimately take place. Of course, there must be enough plasma to carry the co-existing electrical current. However, this is dynamically insignificant. If the electromagnetic field has large scale order and the jet is relativistic, there will be an associated voltage $\sim (L_{\rm jet} Z_0)^{1/2} \sim 1 - 100$ EV, where Z_0 is the effective impedance of free space, $\sim 100\Omega$. Tapping a tiny fraction of this potential difference along a magnetic field line will initiate a discharge of accelerated pairs just like in a pulsar gap (where the potential difference is measured

in TV). In this case particles will be copiously accelerated and cool rapidly close to the black hole. They will also annihilate and a local equilibrium will quickly be established. In general, the partial pressure of the pairs relative to that of the electromagnetic field will increase as the jet expands, though it is hard to be confident about the details. It is quite likely that the flow will automatically become particle-dominated independent of particle acceleration as non-dissipative forces accelerate the plasma. Eventually the jet is likely to entrain ion plasma from its environment and decelerate, again leaving an ion-dominated jet.

The traditional way to investigate jet composition has been to carry out careful polarization observations over a range of radio frequencies so as to measure the Faraday rotation and circular polarization. In principle, a toroidal field wrapped around the jet can be detected using this method and a pair plasma can be distinguished from an electron-ion plasma. Unfortunately, despite much effort, it has only been possible to draw conclusions in a few sources [29] so far. Further studies of more sources, perhaps during γ-ray flares should be instructive.

5. *Understand Jet Confinement*. Jets will naturally expand transversely at some internal sound speed, unless they are confined by the ambient plasma pressure. Close to the hole, the external pressure may be supplied by a non-relativistic wind flowing off the disk. Further away, the jet will ultimately be confined by the interstellar medium and, by the time the jet has escaped the galaxy, stress balance will be maintained by the intergalactic medium. Historically, several confinement possibilities have been entertained. The first and simplest is that jets are not confined at all, that they are freely expanding on a Mach cone, the gas cooling off and the sound speed falling as it flows away from the nucleus. For a relativistic, fluid jet, the Lorentz factor is effectively the Mach number [30]. A problem with this model is that the emissivity would also decline more rapidly with radius than is observed and many jets exhibit morphological features, like "re-collimation shoulders", that are strongly indicative of dynamical interaction with their surroundings. The next possibility considered was that jets were essentially gas dynamical and that the magnetic stresses were smaller than the combined plasma pressure or at least sufficiently chaotic that they could be treated as isotropic when averaged over a large volume. Finally, there is the possibility that jets are magnetic pinches, confined by the "hoop" stress exerted by toroidal magnetic field and stabilized by the supersonic motion of the plasma that it is confining. A magnetically confined plasma will have an associated axial current $\sim (L_{\rm jet}/Z_0)^{1/2} \sim 0.01 - 1$ EA. Ultimately this toroidal magnetic field would have to be confined, either by static or dynamic gas pressure. Put another way, the current that flows up the center of the jet returns along the jet walls. Note, though, that the gas pressure in the centre of the jet can be orders of magnitude larger than the external pressure if there is a magnetic pinch in operation.

   An increasingly promising probe of the magnetic field is provided by the monitoring of optical polarization in blazars. Specifically, a multi-wavelength campaign in 3C279 has found polarization as high as 30 percent suggesting a well-ordered magnetic field. Furthermore, an instance of a correlated, rapid polarization swing of order 200° accompanying a γ-ray flare has also been reported [1]. Even more dramatic behaviour has been seen in PKS 1510+089 [23]. The interpretation of these variations is controversial. They could be due to precessional like motion of a jet at small radius with individual jet elements moving more or less ballistically. Alternatively, a single moving source could follow a helical track at large radius.

Either way, the observations are at least indicative of strong magnetic field, but in order to distinguish kinematical alternative, more data and better simulations will be necessary and are likely to be forthcoming.

The situation with the external confinement is probably clearest for jets associated with rich clusters of galaxies. X-ray observations are now providing fairly precise measurements of gas pressure [16]. There is a debate about how much additional pressure can be associated with turbulence and cosmic rays but the outcome is not likely to change qualitative conclusions. In addition these pressure measurements can be extended into giant elliptical galaxies. A different set of arguments gives pressure and distance estimates for broad emission line clouds within the central parsec of flat spectrum radio quasars.

The task of doing a better job of estimating the pressures inside jets is most approachable at radio frequencies using VLBI observations. However there are complications. It is necessary to correct for the effects of relativistic beaming, though this is less severe than might be expected because the same Doppler effect that boosts the observed flux also leads to a lower comoving brightness temperature and a compensating, larger inferred comoving magnetic field. A second issue is that the regions that are actually observed as superluminally moving features may be transiently over-pressured relative to their surroundings. Nonetheless, it should still be possible to decide if magnetic confinement is obligatory or merely a possibility.

6. *Elucidate the Particle Acceleration*. Understanding the ratio of particle to magnetic pressure within jets has a major impact on deciding which of several particle acceleration mechanisms are at work. As jets expand, the energies of the relativistic electrons (measured in the co-moving frame) decrease and the cooling times of the highest energy, $\sim$ 100 TeV, synchrotron-emitting electrons are much shorter than the expansion timescales. It is clearly necessary to invoke local *in situ* particle acceleration to compensate these losses.

   It has been commonly assumed that electrons are re-accelerated by shocks, but there are several concerns with this idea. In particular, shocks have to be strong to be efficient accelerators and this means that they are likely to be well-spaced and too far apart to sustain continuous emission at the highest synchrotron frequencies. Furthermore, if electromagnetic field accounts for a significant fraction of the pressure, then the shocks cannot be strong in the sense of having a high compression. It is not even clear that relativistic shocks can accelerate particles efficiently enough anyway [28].

   For all of these reasons, alternative acceleration schemes have been considered. It is quite reasonable to expect the jet to be very noisy and permeated by an intense spectrum of hydromagnetic wave modes. These waves can be very efficient at accelerating high energy particles either stochastically or systematically at the gyroresonance. Another possibility is magnetic reconnection. This process is known to be capable of creating surprisingly energetic particles under non-relativistic conditions, albeit with low efficiency. Reconnection is far more promising under relativistic conditions. Although it is far from understood, it remains a strong candidate for the dominant acceleration mechanism, and the total rate of dissipation expected on the basis of simulations is high. There has been much recent progress on kinetic calculations of these various particle acceleration mechanisms [31]. Much more can be expected in the near term.

7. *Infer the Power and Thrust*. Improving our understanding of the local conditions within jets is a step along the way to improving our estimates of jet thrusts and powers. This is a vital input to understanding the relationship between nuclear activity and galaxy formation and evolution. Thrust, of course, is not conserved along a jet, just like in a rocket exhaust. Power is conserved as long as the jet has fixed boundaries which is unlikely to be true. The direct approach to measuring the power and thrust is to estimate the integrals over the cross-section of the jet,

$$\mathcal{L} = \int dA \left[w\Gamma(\Gamma^2 - 1)^{1/2} c + \frac{(\vec{E} \times \vec{B}) \cdot \vec{n}}{\mu_0} \right]$$
$$\mathcal{P} = \int dA \left[w(\Gamma^2 - 1) + P + \frac{(\vec{E} \times \vec{B}) \cdot \vec{n}}{\mu_0 c} \right]$$

respectively, where w is the enthalpy density, P is the pressure and $\vec{n}$ is the unit vector normal to the cross-section element. Note that, as mentioned above, there could be much more kinetic energy and momentum residing in cold protons. However, it is possible to limit this contribution because in relativistic flows, the accompanying electrons, despite being cold in the co-moving frame, will emit inverse Compton radiation.

A major uncertainty in these estimates is that much of the outflow may be invisible. If the hole accretes slowly through a disk and the gas is unable to cool, then the liberated binding energy may be carried away from the disk by a wind. In some sources, especially those with slowly spinning holes, the thrust from non-relativistic, non-radiative disk outflow may dominate that from relativistic, radiative jets. In addition, and somewhat surprisingly, simple models of magnetically confined jets still have power and thrust that are dominated by the mechanical component.

An alternative approach to estimating the power and thrust, at least for powerful sources, is to model the flow within the radio sources and around the "hot spots" at the end of the jets. Of course, one needs to carry out and reconcile this approach with the direct estimates.

Observationally the best prospects for improving these estimates probably lie with the E-VLA. Low frequency observations are crucial because most of the energy density in the relativistic electrons resides at low energies. A clear goal is to relate the estimated jet power to the Eddington limit for the central black hole, now that it is possible to give more confident estimates of the hole mass either from direct dynamical measurements or from application of an $M - \sigma$ relation.

8. *Test the Central Dogma*. It is possible to state a "central dogma" patterned on a powerful principle in molecular biology. This is that the intrinsic properties of AGN, including the radiation that they emit, are predominately a function of three parameters, the mass of the hole (which pretty much sets a scale for length, time, power etc.), the mass supply rate in units of the hole mass, and the angular velocity of the hole in units of the inverse hole mass. Of course this is no more likely to be rigorously true than corresponding statements about stars turned out to be true. Exception had to be made for pre- and post-main sequence evolution, mass transfer binaries and the relatively small effects associated with age, rotation and metallicity. And yet the main sequence in the luminosity temperature plane, or its

proxy, turned out to be a powerful organizing principle. The jet central dogma does not seem to have been seriously falsified as yet but it may be and this would be a powerful further clue as to what additional parameters would have to be considered in devising a "grand unified theory" of AGN.

Some qualifications are in order. Firstly, jets provide a prime example that orientation matters. However, this is not an intrinsic property of the AGN and, in testing the central dogma, it is necessary to remove the effects of beaming (as well as absorption and scattering) from the observations. Secondly, the black hole also defines scales of temperature and magnetic field strength and so the detailed observed spectrum has a non-trivial variation with mass. The radiative cooling is also a sensitive function of temperature. Thirdly, the possibility, discussed above, that a significant fraction of the mass supply to the outermost parts of an accretion disk escapes in a disk-wind before it has time to reach the event horizon of the hole, implies that it is important to distinguish the mass supply rate from the accretion rate.

Here, the way forward includes working on seeing if, as has been widely conjectured, the formation of relativistic jets is a consequence of a low relative mass-supply rate. Can we argue that the radio-loud quasars have mass accretion rates in units of the Eddington rate, that are much smaller than those for the radio-quiet quasars? In addition, understanding if there is a clear distinction between radio galaxies, like Cygnus A, and radio quasars like 3C 273, would be a great advance.

9. *Simulate General Relativistic MHD Jets.* Analytic models of jet formation and propagation are typically axisymmetric, stationary and one-dimensional or self-similar in radius. These are serious limitations and, in order to overcome them, computational models have been developed. The initial models were purely fluid dynamical, axisymmetric and adiabatic, followed by Newtonian and special relativistic MHD models.

   More recently, three (space) dimensional, general relativistic codes have been developed. Early simulations became unstable after a single orbit close to the black hole [20]. However, recently there have been great advances in developing the capability to perform these simulations and it is now possible to run for thousands of m and to explore the development of non-axisymmetric instabilities [14, 18]. It is also possible to understand, at least qualitatively, the influence of black hole spin and the underlying symmetry of the magnetic field in the vicinity of the hole [7, 24]. Electromagnetic energy extraction from a spinning black hole has been convincingly demonstrated [6]. It can be energetically important and lead to the high entropy outflow associated with ultrarelativistic jets. A "dipolar", as opposed to "quadrupolar", field geometry is found to be conducive to jet formation. The simulations are still mostly adiabatic and so the effects of cooling, changes in the equation of state due to quantum electrodynamical processes have yet to be included, but they do affirm that jets can propagate to large radius without disruption, as observed [24].

   Indeed the jet simulations can be extended to radii that overlap those that are probed by radio and, arguably, γ-ray observations. As we describe below, this permits a range of numerical experiments to help understand how the relativistic kinematic properties of moving matter and photons work out in practice in dynamically self-consistent flows. Note that we are not asking whether the jets are due to the black hole spin or the accretion disk – we already know that both are involved, and the debate has moved on.

10. *Quantify Jet Heating of Cluster Gas*. Finally, the challenge that is of most interest to cosmologists, which really depends upon several of the challenges that we have already discussed, is to understand the connection between nuclear activity and the surroundings of the host galaxy. It has long been appreciated that the cooling times of the hot gas in the centres of the richest clusters are shorter than the ages of these clusters [15]. The gas does not appear to be accreting at the high rates that are associated with the cooling, instead it is now thought to be arrested by heating, some of which may be due to jets. However, the nature of the interaction between the outflows and the hot gas is still controversial. The gas seems quite stably stratified, but there are instabilities that can be excited in the presence of magnetic field and heat conduction and these may effectively disperse heat, derived from jets around the cluster. However, it is still hard to see how the consequences of incipient thermal instability can be avoided. It is also not clear how the jet actually does the heating. If we just imagine it inflating a bubble which pushes out the surrounding gas adiabatically and then allows the gas to slowly sink back as the bubble rises buoyantly, then there would be no heating. However, if the Reynolds' number is high enough, the bubble will be followed by a turbulent wake which will increase the cluster entropy. Also the aerodynamic noise associated with the jet can lead to heating, although the excitation of internal waves (as opposed to sound waves) would seem to be more promising.

    The most immediate physical challenge is to characterize the physical behaviour of the cluster gas. Its entropy distribution is measured quite accurately now in several clusters [16] but there is still large controversy concerning the heat conduction both along the magnetic field and perpendicular to the field through field line wandering [25]. Another complication is that the strong shock waves that heated the cluster gas in the first place will also have accelerated relativistic protons which may exert a partial pressure that contributes to the support of the gas. (Indeed the strong accretion shocks that must be present in the outer parts of clusters in order to create the high gas entropies that are measured by the X-ray observations, provide another explanation for the acceleration of Ultra High Energy cosmic rays so long as their composition turns out to be iron.) Relativistic particles are, of course, also released by the radio sources that the jets feed. We may well be on the verge of understanding these questions and if so, this may permit a "reverse engineering" of the jet properties.

3. Flow Simulations

Simulating the dynamics of relativistic jets is a formidable task. There is abundant evidence that they originate close to the event horizon of a spinning black hole. This necessitates working in the background of the Kerr metric, the unique solution to the vacuum Einstein field equations. (Although the black hole will be charged, the magnitude of this charge will be tiny and we do not need to invoke the Kerr-Newman metric which is appropriate when the charge is gravitationally significant [9].) Furthermore we should, at least, be solving the equations of magnetohydrodynamics, not just fluid dynamics. (When the gas is dynamically insignificant and relegated to the roles of supplying the current and carrying the electrical charge, we can make do with the relativistic force-free equations.)

As remarked above, it is necessary to carry out non-axisymmetric simulations as assuming axisymmetry may suppress damaging instabilities and present misleading results. In addition, too short a run may also mislead as it can reflect the transient response to an artificial initial setup and not characterize the quasi-steady properties of jets. Fortunately,

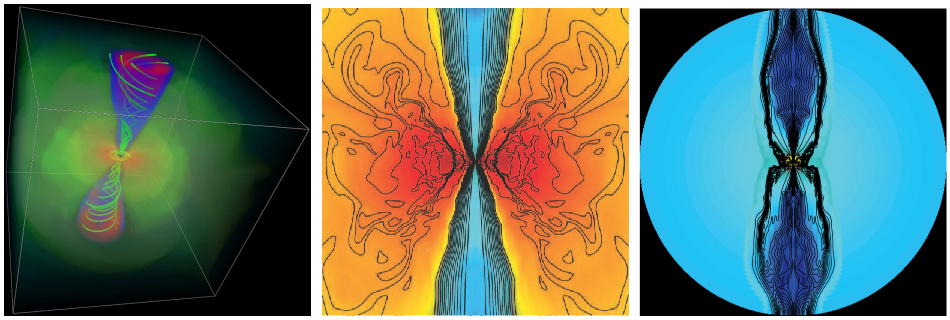

Figure 1. Left: The inner $r < 100m$ for the model described in the text. The isobars are yellow and field lines are green. The log rest mass density of the outer disk and wind is volume rendered, increasing from green to orange and the jet Lorentz factor is volume-rendered up to $\Gamma \sim 4$ increasing from blue to red. Centre: The final distribution of magnetic field overlaid on the logarithm of the rest mass density (blue low, red high) out to $r \sim 100m$. Right: The same out to $r \sim 10^4 m$ for an otherwise identical 2D (space) simulation.

we now have the software and hardware to address each of these concerns in a single run. McKinney and collaborators have undertaken a program of performing three (space) dimensional general relativistic magnetohydrodynamical simulations of magnetized accretion disks orbiting spinning black holes. This formalism is believed to be adequate to describe the bulk properties of these flows. The third dimension is also essential to sustaining the magnetic field in the presence of dissipation [5]. What is typically found is that near the black hole the plasma's rotational, infall, and jet speeds are mildly relativistic and that well-collimated jets are created at large radius that move with ultrarelativistic speeds ($\Gamma \gtrsim 3$) due to conversion of electromagnetic energy into kinetic energy. In one particular simulation [24], used in the analysis that has been completed to date, the HARM code was employed with an effective spherical polar resolution of $r \times \theta \times \phi = 512 \times 768 \times 64$, a spin of $a/M = 0.93$, a disk thickness $H/r \sim 0.2$ and a dipolar magnetic field geometry. Outflows with $\Gamma \sim 10$ were found after the jet expanded out to $r \sim 1000m$ with a scaling of roughly $\Gamma \propto r^{1/2}$ with jet efficiencies $L_{\rm jet}/\dot{M}c^2 \sim 0.01$. The potentially destructive non-axisymmetric ($|m| = 1$) instabilities only achieve modest amplitude and there is still little dissipation.

The character of a jet is clearly dependent upon important boundary conditions which may be captured ultimately by two parameters, the dimensionless accretion rate, which controls the disk radiative efficiency and thickness, and the spin which may control the electromagnetic power. In addition, the large scale field geometry can have a large influence on the stability. Hybrid simulations that combine the most sophisticated features of separate jet and disk computations and studies of parameter space are underway. Much has been learned already and even more is imminent as more and longer simulations are performed. The most important conclusions are that bipolar jets can maintain their integrity and attain asymptotic Lorentz factors $\Gamma \sim 5$ under a broad range of external conditions and that energy can be extracted electromagnetically and stably from a spinning black hole, despite expressed concerns about the stability of this process. Confining magnetic field lines are wrapped around the outflows as envisaged and the flow emerging from just outside the event horizon is electromagnetically-dominated whereas that from disk is mass-loaded and slower. Nonetheless, the jets are subject to moderate amplitude instabilities, especially helical modes related to the polarization swings mentioned above. Quadrupolar jets seem to disrupt, a behaviour that can be traced to the biconical current sheets that must form within the ergosphere.

4. Observing Simulated Jets

As should be clear from the foregoing challenges, there is an explosion in the amount of observational data on jets. It is also clear that computational astrophysicists now have the capacity to explore a wide variety of possible dynamical and emission assumptions, and increasingly sophisticated treatments are possible. These two endeavours - analysis and simulation - ought to confront each other in statistical analyses. In order to further this goal, we have initiated some preliminary simulations of observations of relativistic outflows based upon accurate MHD simulations. Modeling the observed emission requires

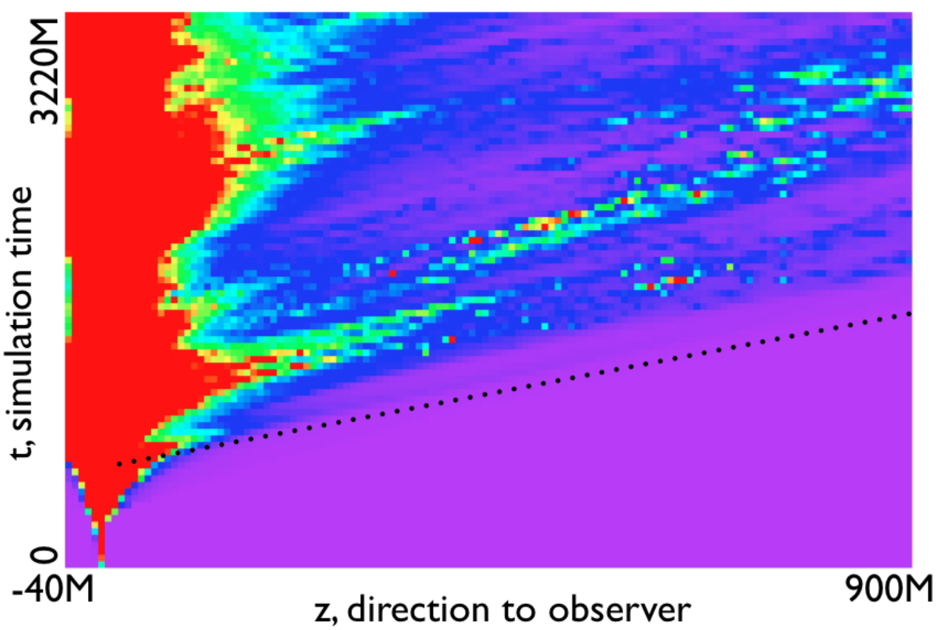

Figure 2. To produce integrated light curves, we first integrate emissivities in the direction perpendicular to the line of sight z, which is possible because the emission from these locations reaches the observer simultaneously. The equation of radiative transfer is then solved along the lines of $z = ct + const$ (an example is shown with dots in this $z - t$ diagram) to account for propagation effects.

additional assumptions to be made about the particle acceleration, which is poorly understood, and the consequent emissivity and radiative transfer, which is straightforward in principle. In a pilot project to model synchrotron emission from a jet, we have taken the output from one particular 3D MHD simulation which presents gridded data on the gas pressure, magnetic field, particle density and velocity at a sequence of times, and used these variables to assign emissivity to fluid elements in the jet. The simplest prescriptions are those in which a fixed fraction of the gas pressure or the magnetic energy density are converted into synchrotron-emitting non-thermal particles. More physically motivated prescriptions include those with non-thermal pressure proportional to velocity shear or Ohmic dissipation, and those in which the presence of non-thermal particles is tied to the direction of the magnetic field relative to the local velocity. In all these cases, the simplicity of the approach lies in the assumption that the emissivity is only dependent on the local parameters of the flow – this would be the case if the cooling time of the particles under consideration were shorter than the typical propagation times. The logical next step would be to consider particles with longer cooling time; in that case, accumulation and cooling of non-thermal particles would need to be tracked for each fluid element as it propagates and its parameters evolve. After evaluating emissivity into each polarization

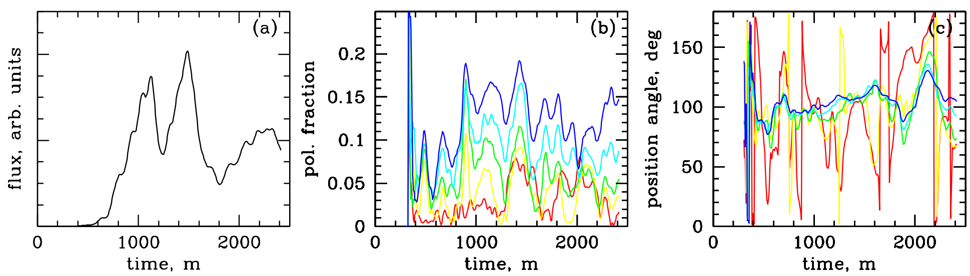

Figure 3. Panel (a) shows a typical lightcurve due to optically-thin synchrotron emission from the jet as measured by a distant observer. Panels (b) and (c) show the variations in the measured polarization fraction and position angle. When the jet is viewed on-axis ($\theta = 0$, red), its magnetic field is in a roughly centro-symmetric pattern on the sky. As a result, the polarization averages out, the measured degree of polarization is low, and small brightness enhancements in different parts of the jet lead to rapid changes of the polarization position angle. As the viewing angle is increased (from yellow to blue, $\theta = 2.5^{\rm o} - 10^{\rm o}$), the magnetic field of the jet appears more ordered as projected on the plane of the sky, polarization fraction increases and the polarization position angle stabilizes to reflect the dominant component of the magnetic field.

state in the co-moving frame using the "local emissivity" approach, we conduct radiative transport in the observer's frame, taking into account Doppler boosting and polarization aberration effects. The spatial grid is rotated so that the observer is directed along the z direction. Because of the non-static nature of the problem, the emissivities of the elements further away from the observer need to be evaluated at an earlier time to account for the propagation effects. Synchrotron self-absorption is also best handled in the observer's frame. At radio wavelengths, synchrotron absorption is very important, and the entire simulation volume lies within the optically-thick "core", whereas emission at visible wavelengths is optically-thin. As described above, optical polarization is emerging as a very important diagnostic, and the changes in polarization (including rapid "polarization swings" detected in the simulations) depend sensitively upon the orientation of the observer relative to the jet.

The next steps are to add γ-ray opacity and compute the associated fluxes, sample all observer directions and loop over different jet simulations. A prime goal is to compute statistical correlations of emission at different wavelengths both within a single source and also over a population of sources. It appears that new observational data, which will be forthcoming over the next few years, will be able to discriminate between radically different jet models currently under consideration. A fuller description of these simulations is in preparation.

5. Summary

In this brief account, we have attempted to show how our understanding of a common astrophysical phenomenon - relativistic jets - is improving and, in particular how it should improve in the future. We have highlighted phenomenology and simulations as the promising approaches for elucidating the physics of black hole jets. It is striking that the theoretical foundations of all of these investigations are rooted in his deep and extensive explorations of general relativity, MHD and radiative transfer and would not have been possible without all experience that was gained by Chandra and his colleagues though their prescient and systematic solutions of so many theoretical problems. For that, we all remain in Subramnayan Chandrasekhar's debt.

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