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COSMIC RADIO JETS

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Abstract. Extragalactic radio sources, including quasars, are now typically understood as being produced by a pair of nearly symmetric, oppositely directed relativistic jets. While some these sources span megaparsecs, and are thus the largest physically connected structures in the universe, emitting regions identified as jets have now been found on all scales down to fractions of a parsec, and jets appear to be a common element of most (maybe all) types of active galactic nuclei (AGN). We first summarize key observations of different classes of cosmic radio jets, and describe how they may be connected. Theoretical models for the launching and propagation of extragalactic jets are briefly described. All of these models assume a magnetized plasma, which typically amounts to only a small fraction of the accreted gas, is ejected from the vicinity of a supermassive black hole. The extreme complexity of the relevant physics has demanded numerical simulations to examine non-linear effects on the stability of propagating jets, and some recent results from these efforts are summarized.

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1. INTRODUCTION: ‘‘ANCIENT’’ HISTORY

The discovery of extragalactic jets must be considered one of the triumphs of astrophysics, as it involves one of the relatively few actual *predictions* in this fundamentally observation driven science. Early radio telescopes revealed the existence of extragalactic double radio sources such as Cygnus A (Jennison & Das Gupta 1953), and led to the discovery of quasars in the 1960’s. The combination of

non-thermal, essentially power-law, radio spectra, and often substantial polarization, very quickly led to the emission mechanism being identified as synchrotron radiation from relativistic charged particles in helical orbits around magnetic field lines. In the early 1970's a few theoretical papers (Rees 1971, Longair et al. 1973, Scheuer 1974, Blandford & Rees 1974) proposed that these extremely large (typical scales of 100 kpc) and powerful (typical $L_{\rm R} \sim 10^{44}\ erg\ s^{-1}$) sources were fed by jets emerging from the centers of elliptical galaxies. Only with the dynamic range provided by the Very Large Array and other radio telescopes coming on line later in the 1970's were many of these jets actually detected. Competing models, involving blobs (or ''plasmoids'' or ''plasmons'') of radio emitting plasma (e.g., Pacholczyk 1977) or gravitational-slingshots that eject independent engines and sources of plasma (e.g., Saslaw, Valtonen & Aarseth 1974) are now rarely considered. This is because of the convincing evidence of nearly co-linear emission extending from less than a pc to hundreds of kpc in many sources. While we shall not discuss these alternative scenarios any further, it is still worthwhile to note that many of the observations of radio galaxies can be accounted for by the slingshot model (Valtonen & Heinämäki 1999).

The vast majority of these extragalactic radio sources can be easily classified into one of two categories, as first noted by Fanaroff & Riley (1974), who carefully examined the first set of synthesis maps. The weaker ones, or FR I's, with radio fluxes $P_{178\rm MHz} < 2 \times 10^{25}\ h_{50}^{-2}$ W Hz^{-1} sr^{-1} (where h_{50} is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}), tend to have their brightest regions within the inner half of the total extent of the radio source; i.e., much of the flux emerges from the jets themselves, and the fluxes emanating from the two jets are almost always comparable. The FR I sources can be further sub-classified into fairly symmetrical twin-jets, Wide Angle Tail, and Narrow Angle Tail (or head-tail) sources (e.g., Bridle & Perley 1984). Many of the details of these diverse structures can be understood in terms of interactions of the jets with the motions of, or irregularities in, the density and magnetic fields of the external media (interstellar, intracluster and intergalactic) through which they propagate. Other FR I morphologies, particularly S-type symmetries, could be explained by the precession of the jets axes or ejection of the jets from one component of a binary AGN.

More powerful sources, or FR II's, emit the bulk of their radio photons from the outer portions of their structures. Almost all of these are the classical double sources, with most emission coming from lobes which are usually well separated and extend outside the stellar extent of their host galaxy. These lobes contain hot spots near their outer edges. The hot spots are identified with the locations where the bulk velocities of the jets undergo rapid deceleration in shocks (Mach disks); the magnetic fields are compressed in these shocks and the individual electrons (and perhaps positrons and/or protons) are accelerated to very relativistic speeds at those locations, thereby explaining the extraordinary emissivities (e.g., Blandford & Rees 1974). Only very careful observations allow the detection of a jet in FR II sources since they are often thousands of times weaker than the lobes; very seldom is a second (counter-)jet found. These FR II jets are usually very well collimated in comparison with FR I jets (e.g., Jeyakumar & Saikia 2000).

Readers interested in more thorough discussions of most of these topics should first consult the older, but still very useful, reviews of Bridle & Perley (1984) (primarily for the observations), and Begelman, Blandford & Rees (1984) (primarily for the theory). A superb summation of the entire subject can be found in the volume edited by Hughes (1991) and a substantial recent review is by Ferrari (1998). Many excellent conference proceedings could be consulted, including those edited by Hardee et al. (1996), Biretta & Leahy (2000) and Laing & Blundell (2001). In light of the availability of these summaries, only a limited number of classical contributions will be cited in this review, which emphasizes some new work selected from a vast literature.

Radio emitting jets have also been identified emanating from a few binary systems within our Galaxy; these have been dubbed ''microquasars''. In addition, jets have been found emerging from many protostars. This brief review cannot discuss these local manifestations of jets; the reader interested in relativistic jets within our galaxy should consult an excellent recent review by Mirabel & Rodríguez (1999).

2. SOME KEY OBSERVATIONS AND IMPLICATIONS

2.1. Properties of extragalactic jets

The fact that synchrotron emission does not provide spectral lines has meant that even the simplest facts about the properties of jets, such as their velocities and compositions, have remained controversial. While magnetic field structures can be directly probed through polarization measurements, estimates of magnetic field strengths can usually only be made through the assumption of equipartition between the energies in the radiating relativistic particles and the magnetic field energy density; this assumption has the advantage of minimizing the total energy that needs to be supplied to the radio source.

Evidence for relativistic bulk motion in the powerful FR II sources has been generally accepted for quite a while, mainly because of the detection of apparent superluminal expansions of pc-scale knots through Very Long Baseline Interferometry (VLBI), along with the detection of fast motions on substantially larger spatial scales in a few sources. A source of radiation moving at moving with velocity $\beta = v / c$ at an angle, θ to the line-of-sight will have an apparent transverse velocity, $\beta_{app} = (\beta \sin\theta) / (1 - \beta \cos\theta)$, which can exceed 1 if $\beta \gtrsim 1$ and θ is small. Very fast motions, implying bulk Lorentz factors, $2 < \Gamma = (1 - \beta^2)^{-1/2} < 10$, also naturally explain the substantial asymmetry in the radio emissivities of extended jets in FR II sources; the jet with a component towards us would be Doppler boosted, while the (usually unobserved) counter-jet would be Doppler dimmed. For a jet of intrinsic spectral index α [defined so that $S_{em}(\nu') \propto (\nu')^{-\alpha}$] the observed flux would be (e.g., Scheuer & Readhead 1979), $S_{obs}(\nu) = S_{em}(\nu) D^{(2+\alpha)}$, where the Doppler factor, $D = [\Gamma (1 - \beta \cos\theta)]^{-1}$], and the observed frequency is related to the emitted one by $\nu = \nu' D$; for small θ , this implies large enhancements. For a single source, the exponent in the above equation becomes $(3 + \alpha)$, and the boosting effect is even more pronounced. Apparently abrupt changes of directions of jets on the VLBI scales are also naturally explained in terms of small intrinsic direction changes that appear magnified to distant observers by special relativistic effects. Since the fluxes from the opposite hot-spots and lobes are usually very similar in FR II sources, it is widely accepted that the bulk motions of those extended regions are non-relativistic, with typical head advance speeds of ~ 0.03*c* (e.g., Scheuer 1995).

Recent observations have found that many FR I jets also provide evidence of relativistic velocities on VLBI scales (e.g., Giovannini et al. 1994, Biretta et al. 1999, Xu et al. 2000). Doppler boosting can not only explain that powerful FR II jets appear one-sided, but also that weaker FR I jets exhibit large brightness asymmetry only near their origins, and typically have short, one-sided basal regions (e.g., Laing et al. 1999; Kharb & Shastri 2001). The evidence that FR II jets retain relativistic bulk velocities out to 100's of kpc is quite convincing, with the brighter large scale jet always seen on the same side as the nuclear jet and towards the less depolarized radio lobe (e.g., Garrington et al. 1988, Bridle 1996, Gopal-Krishna & Wiita 2000a), so that it is inferred to be approaching us. However, for FR I jets, their diffuse morphologies, the fact that the brightness asymmetry of the jets decreases with increasing distance from the core, and substantial large bends frequently seen in FR I jets at multi-kpc

scales imply that much slower flows ($v_{\rm bulk} < 0.1c$) exist on larger scales (O'Dea 1985, Feretti et al. 1999, Laing et al. 1999).

It is universally accepted that most, if not all, of the synchrotron emission arises from relativistic electrons. But the nature of the main positively charged component of the jet plasma remains contentious. Until recently, the great majority of workers have assumed that protons provided that neutralizing matter, and that their much greater masses implied that they required a lot of extra energy to accelerate but that they provided very little radio emission. However, the possibility that the jet was really composed of an e^+-e^- plasma has been suggested for a long time (e.g., Kundt & Gopal-Krishna 1980). Application of total energy and synchrotron radiation constraints led Celotti & Fabian (1993) to conclude that FR II jets were made of e^--p plasma, since they argued that e^--e^+ plasma of the required density would yield too much annihilation radiation. However, Reynolds et al. (1996b) used similar energetic and radiation constraints to conclude that the jet in the FR I source M87 was likely to be made of e^--e^+ plasma. A similar argument favors an electron-positron jet in the Optically Violently Variable Quasar 3C 279 (Hirotani et al. 1999). If all of these arguments are taken at face value, one might infer that the main difference between FR I and FR II sources lies in the composition of the jet plasma, and this would imply the existence of a fundamental difference between their central engines. But it is worth noting additional evidence for the presence of pair plasma jets, even in FR II sources, comes from the interpretation of the radio power-linear-size (P-D) diagram in terms of a model for quasi-self-similar growth of double radio sources (Kaiser et al. 1997).

Although there are exceptions to this rule, it is well established that, in general, the magnetic field in a FR II jet remains aligned with the jet along most of its length, while in a FR I jet the magnetic field is predominantly transverse on multi-kpc-scales (e.g. Bridle & Perley 1984). Careful studies of FR I jets have led to the conclusion that the asymmetries in apparent emission from the two jets, and their detailed magnetic field patterns, are best explained if the jets in these sources consist of a narrow ''spine'' of relativistic flow with a predominantly transverse magnetic field, surrounded by a slower moving ''sheath'', probably contaminated by entrained material (a shear layer) where the magnetic field is stretched into a predominantly longitudinal configuration (e.g, Laing et al. 1999).

2.2. The Fanaroff-Riley Dichotomy

There are many other observed differences between FR I and FR II radio sources and the galaxies that host them (e.g., Baum et al. 1995, Zirbel 1997, Gopal-Krishna & Wiita 2000b). All these observations have led to the development of two general classes of explanations for the Fanaroff-Riley dichotomy.

Intrinsic explanations involve a fundamental difference in the central engine or jet properties between these two classes, while extrinsic explanations claim that the differences arise through interactions of the jets with the media through which they propagate. Among the intrinsic explanations are (see Gopal-Krishna & Wiita 2000b for details and many more references): the difference in jet composition mentioned above; a difference in the central engine, such as having a more rapidly spinning black hole yield FR II jets (e.g. Wilson & Colbert 1995, Meier 1999); a difference in the accretion process, where advection dominated flows might yield FR I jets, while more luminous ''standard'' accretion disks might produce FR II jets (e.g. Reynolds et al. 1996a).

The various extrinsic explanations assume that the jets differ in little except total power or thrust. In these scenarios, deceleration of the jet, through growth of instabilities and/or entrainment of external plasma, converts weaker jets into FR I morphologies, while stronger jets, which remain supersonic and/or relativistic to great distances, produce FR II structures (e.g., Bicknell 1984, 1995, Komissarov 1990). Recently Gopal-Krishna & Wiita (2000b) have stressed that the existence of a small number of sources with distinctly FR I morphologies on one side of the core and FR II morphologies on the other

side, can play an extremely important role in distinguishing between these putative explanations for the FR dichotomy. They have found six good examples of these HYbrid MOrphology Radio Sources, or HYMORS, and have argued that while they are expected to be rare if an extrinsic mechanism dominates, HYMORS are unlikely to be found at all if an intrinsic mechanism were to be important.

As more measurements were made of the galaxies that host radio jet sources, it became clear that the simple radio source power criterion found by Fanaroff & Riley was not really appropriate. Rather, as the luminosity of the host galaxy, $L_{\rm opt}$ grows, so does the radio power, $P_{\rm R}^{\ *}$, required to produce an edge-brightened, FR II, morphology. This was quantified by Ledlow & Owen (1996), whose extensive data compilations showed that $P_{\rm R}^{\ *} \propto L_{\rm opt}^{\ 1.7}$. Bicknell (1995) demonstrated that this relation could be roughly reproduced within an extrinsic model for the FR dichotomy; in this picture, the weaker jets would slow until $\Gamma \simeq 2$ and then suffer the growth of instabilities that lead to FR I type structures. It has now been shown that a variant of this scenario, using a somewhat different jet propagation model (Gopal-Krishna et al. 1989), and where the trigger that yields FR I structure is now the slowing of the advance speed of the jet to subsonic with respect to the external ambient gas (Gopal-Krishna et al. 1996), can produce an even better fit to the observed $P_{\rm R}^{\ *}$ - $L_{\rm opt}$ relation (Gopal-Krishna & Wiita 2001). While both the magnetic-switch model (Meier 1999) and the gravitational slingshot model (Valtonen & Heinämäki 1999) can also yield rough agreements with the radio-optical correlation, given the additional evidence from the existence of HYMORS, it is clear that extrinsic explanations for the FR dichotomy are more likely to be correct.

2.3. Implications of Relativistic Motions

As mentioned in Section 2.1, the detection of apparently superluminal transverse motions provides extremely strong evidence for relativistic motions in jets, and these large Γ values also provide an excellent explanation of the preponderance of asymmetric jet luminosities in double radio sources with quite similar lobe powers. The orientation at which we view these relativistic jets can also provide an understanding of several other key features of radio-loud AGN.

It is now widely accepted that AGNs with strong radio jets will typically be classified as radio galaxies if the orientation of the jet to our line-of-sight to the source is greater than a critical value, $\theta_{\rm crit} \simeq 40°$, while the same source will be called a quasar if $\theta < \theta_{\rm crit}$ (e.g., Barthel 1989; Urry & Padovani 1995). These unified models for radio-loud AGN assume that the jets are launched parallel to the rotation axis of a supermassive black hole (SMBH) and perpendicular to the accretion flow feeding the SMBH. Unified models also require the presence of a thick dusty torus outside the accretion flow (on the scale of several parsecs) that can absorb enough soft X-ray, UV and optical radiation to hide both the direct core continuum emission and the broad emission line region if viewed from angles above $\theta_{\rm crit}$.

In addition, if the jet is very close to our line of sight ($\theta \simeq \Gamma^{-1}$) then very substantial special relativistic effects would strongly enhance the observed fluctuations and polarization. Under these circumstances the source might be classified as an Optically Violently Variable quasar or other type of blazar. Extremely convincing explanations for the variations on the timescales of months of several quasars in terms of shock-in-jet models have been available for quite some time (e.g., Marscher & Gear 1985, Hughes, Aller & Aller 1991), and very rapid variability and polarization swings can be understood if the shocks are travelling down a slightly bent jet (e.g., Gopal-Krishna & Wiita 1992) or if there is strong turbulence in the vicinity of the shock (e.g., Marscher & Travis 1991). Recent measurements indicate that much of the fastest (intraday) radio variability (see Wagner & Witzel 1995 and Wiita 1996 for reviews) is probably due to interstellar scintillation (ISS; Rickett 1990); two such sources are PKS 0405-385 (Kedziora-Chudczer et al. 1997) and J1819+3845 (Dennett-Thorpe & de Bruyn 2000).

Nonetheless, extremely rapid intrinsic variations do appear to be required for some sources. One example is the BL Lac object 0716+714 where there appears to be a correlation between variations in the radio and optical bands (Wagner et al. 1996). Another case is the gravitational lens system B0218+357 (Biggs et al. 2001); here correlated variations between the two images over a few days are seen to be nicely separated by the 10.5 day time lag due to lensing, and cannot be explained in terms of ISS or gravitational microlensing (Gopal-Krishna & Subramanian 1991).

Turning to the weaker radio sources, there is now abundant evidence that FR I radio galaxies are the parent population for BL Lacertae objects, in the sense that a typical FR I source, if viewed at small θ, would show the properties of a blazar, and that the relative numbers of these classes are nicely understood if this unification holds (e.g., Urry & Padovani 1995). The synchrotron self-Compton mechanism can neatly explain the overall spectral energy distribution of blazars (e.g., Sambruna et al. 1996), but this only works if $\Gamma > 5$, for otherwise X-rays would be over produced. Intrinsic variability in many blazars implies small linear sizes; these translate into brightness temperatures that substantially exceed the inverse Compton limit of $\sim 10^{12}$ *K* for incoherent synchrotron sources unless similarly high values of Γ are invoked.

As the sensitivity and dynamic range of radio observations have continued to improve it has become clear that many so-called radio quiet AGN are actually radio weak, but not radio silent, and that there is a considerable population of radio-intermediate sources (e.g., White et al. 2000). Quite a few Seyfert galaxies are now known to possess radio jets, though they tend not to propagate very far, probably because of more rapid disruption by the interstellar medium of their spiral hosts (e.g., Pedlar et al. 1993) Again, a unified scheme seems to work very well, with the Seyfert 1 galaxies viewed at $\theta < \theta_{crit}$ so the broad line region and soft X-rays can be seen directly, while the Seyfert 2 galaxies are viewed at $\theta > \theta_{crit}$ and broad lines can only be detected in polarized reflected light (cf. Antonucci 1993).

3. ANALYTICAL MODELS FOR JETS

3.1. The launching of extragalactic jets

While several implications from the observations of extragalactic jets based on fundamental theories have already been described, we now turn to matters less accessible to direct observation because they occur on such minute spatial scales. Here we have space to merely list some of the ever growing lines of evidence that have convinced essentially all astrophysicists that accreting SMBH's provide the prime mover for AGNs: accretion into a very deep potential well is the only mechanism that appears to be sufficiently efficient (easily > 5%) in converting matter into the energy to power the most luminous AGN; fast luminosity variations imply most of the emitted power must emanate from a very compact region, probably just a few $r_g = GM / c^2 = 1.5\ (M_{BH} / M\odot)$ km in extent; a SMBH, particularly a rotating one, is the only known way to produce the stable axis needed to produce jets extending for Mpc that must have remained active for > 10^7 years; VLBI measurements have shown collimated emission to have been produced within < $100 r_g$ in a few nearby radio loud AGN; stellar velocity dispersions in the inner cores of nearby AGN rise very steeply towards the center, implying immense densities of matter (> 10^7 $M\odot$ pc^{-3}); maser emission lines have demonstrated clear Keplerian rotation about massive dark cores; the shapes of x-ray emission lines are best explained as emerging from the inner portions of accretion disks around SMBHs, where general relativistic effects play important roles.

We now proceed to a brief discussion of the various classes of models that have been proposed to produce jets from the environs of a SMBH. The fundamental types of models proposed through the 1980's for the origin of jets were reviewed extensively by Wiita (1991), and here we will very briefly summarize those scenarios and note some more recent results. All models involve the expulsion of a certain fraction of the matter being accreted by the SMBH. The key distinction between the major classes of jet launching scenarios is whether or not magnetic fields are assumed to be primarily responsible for the expulsion of jet plasma.

Purely hydrodynamical models based upon winds from standard thin accretion disks (e.g., Shakura & Sunyaev 1973) have difficulties in accelerating substantial amounts of matter to relativistic velocities. Crudely, the maximum velocity of an outflow depends upon the depth of the potential well in the region from which the matter is expelled, so if the matter is launched from a significant portion of the disk, then much of it will have relatively low velocities. Such a wind may be able to provide additional collimation to a jet propelled from the innermost region of the AGN (e.g., Sol et al. 1989) but is unlikely to provide either sufficient collimation or sufficient velocity to explain the observations of VLBI scale extragalactic jets.

At very high accretion rates (comparable to or above that required to produce the Eddington limit) radiation supported thick accretion disks can form (e.g., Paczynski & Wiita 1980). This type of accretion flow provides narrow funnels and a more centrally concentrated region from which to launch the plasma, so it had promise to be a reasonable way to produce powerful collimated beams. This type of flow could produce super-Eddington luminosities but involved quite low efficiencies, as much of the emitted radiation was swallowed by the central black hole in an extremely optically thick flow. However, once the matter gets to mildly relativistic speeds, the aberrated radiation actually produces a drag on the outflow and prevents Γ values much in excess of 2 (e.g., Narayan et al. 1983). It might be possible to avoid this limit and attain $\Gamma \sim 10$ if clouds of electrons are present in the flow region; if they can produce enough synchrotron self-absorption of the radiation from the funnel, the red-shifted photons will be unable to decelerate the flow (Ghisellini et al. 1990).

Over the past decade other versions of low efficiency accretion flows, which can occur for very low accretion rates, have been frequently discussed. Early proposals along these lines (e.g., Ichimaru 1977, Rees et al. 1982) have been developed along different directions by Chakrabarti (e.g., 1990, 1996) and by Abramowicz, Lasota, Narayan and collaborators (e.g., Narayan et al. 1998). Aside from its fundamental importance as a way of treating more general non-Keplerian accretion flows, the main rationale for the of study of these advection dominated flows was to explain the spectra of X-ray binaries in different states and to fit the spectrum of radiation emerging from non-active galactic nuclei, such as that in our Milky Way. Recently, variants on these models have been shown to accommodate substantial outflows (e.g., Begelman & Blandford 1999). When the velocity structure is sub-Keplerian, as should happen under a wide range of accretion flows in the near vicinity of the BH, then the flow can quite naturally lead to a centrifugal pressure supported boundary layer, which has been shown to be capable of launching significant outflows (Das 1998, Das & Chakrabarti 1999). This mechanism appears to be able to produce adequately relativistic outflows of reasonably good collimation. However all of these fundamentally hydrodynamical (HD) models make one or more critical simplifying assumptions, and their robustness and range of applicability remain to be tested.

While the last mentioned HD launch mechanisms do appear to be promising they have not yet been studied intensively, and at this point a large majority of workers in this area consider that magnetic fields have an important role to play in the ejection and initial collimation of flows from the vicinities of SMBH's. The fact that jets emit via the synchrotron mechanism makes it clear that magnetic fields are present, and several plausible ways to use magnetic fields to accelerate and collimate flows have long been known.

The advantage of magnetic acceleration mechanisms is that they can simultaneously and naturally produce relativistic velocities, narrow jets and large momentum fluxes. The idea that jets were predominantly a Poynting flux with little mass loading was proposed by Rees (1971), and the possibility that powerful currents could be generated in accretion flows which would then accelerate collimated outflows was first noted by Lovelace (1976). Other pioneering works in this area were by Bisnovatyi-Kogan & Ruzmaikin (1976) and Blandford (1976).

An enormous number of variants on magnetically accelerated jet models have been put forward over the past quarter-century, and we cannot even begin to summarize this literature here. But the majority of them fundamentally rely on either extracting energy and angular momentum through magnetic fields anchored in the disk (e.g., Blandford & Payne 1982; BP), or by extracting the spin energy of the black hole itself, through magnetic fields threading its horizon (e.g., Blandford & Znajek 1977; BZ).

An excellent introduction to the physics of magnetohydrodynamical (MHD) jet production mechanisms is the review by Spruit (1996). The vast majority of this research effort has naturally concentrated on ideal MHD models (where the plasma is tied to the field lines) and makes the simplifying assumptions of stationary and axisymmetry flows with infinite conductivity. While the MHD assumption does not always hold around pulsars, and the low temperatures around protostars imply that finite conductivity can be important there, for the conditions around BHs both of these assumptions should be excellent. Spruit (1996) shows that the centrifugal (beads-on-a-wire) approach of, e.g., BP, and the purely magnetic approach of, e.g., Lovelace et al. (1987) are completely equivalent.

The self-consistent computation of MHD flows is extremely difficult because of the possible presence of multiple critical points, each of which can be associated with a shock, which can be of either the slow- or fast-type (e.g., Heyvaerts & Norman 1989). The types and locations of these critical points depend sensitively on the assumptions made about boundary conditions and initial topology of the magnetic fields. Nonetheless, a variety of initial conditions and analytical approaches have been explored and do provide some general conclusions. MHD jets can collimate asymptotically to a cylindrical structure if they carry a sufficient net current, whereas they are very likely to attain a paraboloidal cross-section if they do not (e.g., Chiueh et al. 1991). Self-confined equilibria can be achieved and analytically described in sensible approximations (e.g., Appl & Camenzind 1993).

A recent generalization of the Blandford-Payne model allows for a hotter initial plasma and finds solutions which start with a sub-slow magnetosonic speed and subsequently cross all critical points, at the slow magnetosonic, Alfvén and fast magnetosonic separatrix surfaces (Vlahakis et al. 2000). These models tend to over-collimate toward the jet axis, as do many other MHD calculations, so it is clear that some of the assumptions going into these models must be relaxed. Such relaxation can best be accomplished through the numerical modeling to be discussed in Section 4.1.

It is worth recalling that extraction of the spin energy of the SMBH through very low accretion rates coupled to magnetic fields is an alternative to unified models as a way of understanding the differences between radio galaxies and quasars (Rees et al. 1982). Recently the underpinnings of the basic BZ mechanism have come under renewed investigation. Ghosh & Abramowicz (1997) have argued that magnetic field strengths in the inner parts of accretion disks are weaker than estimated earlier so that the strength of the BZ process for the extraction of the rotational energy of the black hole is lower than imagined previously. Livio et al. (1999) argue that the magnetic fields threading the BH should not be stronger than those in the inner parts of the disk, so that the BZ mechanism should always contribute less power than the disk feeding it. However, if the field strength continues to grow in the innermost disk region and if plasma plunging into the BH exerts a strong torque on the innermost portion of the disk, as has been suggested recently (Krolik 1999, Agol & Krolik 2000), then

these caveats may be weakened. Furthermore, it is worth noting that the standard BZ flow is likely to be subject to a screw-instability which can limit the extent out to which it can produce plasma acceleration (Li 2000a). However, a related scenario, where magnetic field lines connect plasma particles inside the ergosphere of a Kerr BH with remote loads, is of real interest. Frame dragging twists the field lines so that energy and angular momentum are extracted from the plasma particles, and if the magnetic field is strong enough, then the particles can have negative energy as they fall in, thereby allowing extraction of the BH's rotational energy (Li 2000b). In all of these efforts certain crucial, and not yet adequately justified, assumptions must be made; therefore, none of the specific MHD launch mechanisms can be considered to be convincing, though many remain plausible.

3.2. The propagation and stability of extragalactic jets

Once launched, the key question becomes: can these theoretical jets survive to the distances demanded by observations, where jet hot-spots are often much narrower than 1% of the jet length? Stability analyses of hydrodynamical jets began with discussions of the Kelvin-Helmholtz (or two-stream) instability which showed that faster jets, particularly relativistic ones, could survive longer (e.g., Turland & Scheuer 1976). Important early contributions were made by Hardee (e.g., 1982, 1987), Birkinshaw (1984), Ferrari et al. (1980), Bodo et al. (1989), among others. Then the analyses were expanded from two-dimensional cylinders to two-dimensional slabs, which can mimic some three-dimensional effects (e.g., Hardee & Norman 1988), to three-dimensional hydrodynamics (HD); then, various assumptions about magnetic field geometry have been studied within an ideal MHD framework.

The ordinary mode ($N = 0$) is always excited whenever there is a boundary between a flow and a static region. However, various reflection modes ($N > 0$), which exhibit N pressure nodes within the jet, can also be excited if the walls of the cavity can vibrate coherently; effectively, the sound waves hitting the boundary at an angle can constructively interfere within the jet. Under plausible circumstances the $N = 1$ mode can grow faster than the $N = 0$ mode. Very typically, the dominant modes in 2-D are those with wavelengths of $\sim 5R_j$, and these lead to growth lengths of $\sim 3M\,R_j$, where R_j is the jet radius and M is the Mach number of the jet (with respect to its internal sound speed). The growth of both pinch ($m = 0$) and kink ($m = 1$) modes can be quite fast, but jets with smooth transverse velocity gradients are more stable.

The stability properties of MHD jets have been recently addressed by many authors. Jet magnetic field geometries that evolve into primarily concentric toroidal structures are usually most unstable to kink ($m = 1$) instabilities (Begelman 1998). A study of rotating jets confined by toroidal fields has shown that rigid rotation tends to stabilize, while differential rotational destabilizes, the jet in a way similar to the magneto-rotational instability which is now believed to dominate viscosity production in accretion disks (Hanasz et al. 2000). In this local analysis, if the azimuthal velocity exceeds the Alfvén azimuthal speed, the rigidly rotating part of the jet interior can be completely stabilized, while the strong shearing instability acts on the layer between the rotating jet interior and the external medium, perhaps thereby explaining the limb-brightening seen in some jets (Hanasz et al. 2000). Other rotating MHD jet models have been recently analyzed for stability by Lery & Frank (2000). These connect to a Keplerian disk and have a complex structure: a dense, current carrying central core; an intermediate magnetically dominated region; and a low density outer region carrying a return current. Another approach to the stability of rotating MHD jets has been taken by Kersalé et al. (2000), who use the ballooning ordering expansion to find that cylindrical configurations can be destabilized by a negative magnetic shear as well as by a favorable equilibrium pressure gradient. They note that rotating jets with vanishing current density along the axis, as well as most non-rotating MHD jet models, would be unstable.

The major shortcoming of all of these analytical models is that they can only compute the linear growth rates of various instabilities under initially regular conditions; if taken at face value, probably no analytically computed jet could propagate stably for 100 kpc or more, yet of course many such extended extragalactic sources are observed. Therefore high-resolution numerical simulations are required to explore the non-linear effects which can provide saturation of the linear instabilities.

4. NUMERICAL SIMULATIONS

A good summary of many results emerging from HD and MHD computations of jets was given in Ferrari (1998). In this section we concentrate on more recent simulations.

4.1. The launching of extragalactic jets

Early efforts to incorporate GR effects in simulations of accretion onto a BH indicated the likelihood of significant outflow, even in purely HD situations (Hawley et al. 1984). However, until very recently, this work and other attempts along the same lines were greatly hampered by severe numerical difficulties. These demanded the development of techniques, such as adaptive mesh refinement, that allow one to efficiently and simultaneously compute flows in the high density regions in the accreting gas and in the low density expelled gas; following the latter also requires much greater spatial scales which make the computations extremely expensive.

Pioneering work on MHD launching of jets from disks was performed by Uchida & Shibata (1985), who evolved an initially vertical magnetic field tied to a cold thin disk rotating around a point mass assuming axisymmetry. Differential rotation in the disk produces a substantially toroidal field and this magnetic tension is released through strong torsional Alfvén waves, which expel mass. This approach has recently been extended to 3-D relativistic flows around Schwarzschild BH's by Koide et al. (1998) and Nishikawa et al. (1999). They find that a shock forms in the disk and yields a gas-pressure driven jet which dominates the outflow, though a weaker MHD jet is present outside the pressure driven jet. In a truly impressive computation, this work has recently been extended to the environs of a rapidly rotating Kerr BH (Koide et al. 2000); while the results for a corotating disk do not greatly differ from those of the Schwarzschild situation, for (the relatively unlikely case of) counter-rotating disks a very powerful magnetically driven jet is formed inside the gas-pressure driven jet.

The launching of cold gas from a disk under circumstances carefully designed to emulate the BP magneto-centrifugal mechanism has recently been simulated in 3-D by Krasnopolsky et al. (1999). If the field is set up to be ''propelling'' then rapid acceleration and collimation of the flow are indeed observed. A simulation of the situation where a Keplerian disk is initially threaded by a dipolar poloidal magnetic field has been recently performed by Ustyugova et al. (2000); they find that a quasi-stationary collimated Poynting jet arises from the inner part of the disk, while a steady uncollimated hydromagnetic outflow emerges from the outer part of the disk. Although these calculations are focussed on the types of overdense cooling jets that are to be found in protostellar systems instead of AGN, it is also worth noting the sophisticated numerical techniques involved in the simulations of Stone & Hardee (2000).

4.2. The propagation and stability of extragalactic jets

Early 2-D simulations of HD jets (e.g., Norman et al. 1982) were of great importance in establishing that extragalactic jets were of very low density and of high Mach number, for the morphology of FR II radio galaxies could only be reproduced under those circumstances. The jet is preceded by a bow shock; the cocoon is comprised of shocked ambient medium, separated by a contact discontinuity from jet material that has passed through a Mach disk shock at the head of the jet, which corresponds

to the hot-spot. Since then, as the largest computers have been turned to this task, the computations have greatly improved in both spatial resolution and temporal duration. Very long term 2-D simulations, which allowed the growth of axisymmetric Kelvin-Helmholtz instabilities to go non-linear (typically after the jets propagated distances corresponding to hundreds of initial radii) indicated that the lobes could become detached from the jets, but that new Mach disks could form behind them, thereby explaining some of the ''double-double'' radio source morphologies (Hooda et al. 1994). A suite of 2-D relativistic and nonrelativistic jets have recently been compared to show that the velocity field of nonrelativistic jet simulations cannot be scaled up to give the spatial distribution of Lorentz factors seen in relativistic simulations, as had been often speculated to be the case (Rosen et al. 1999); however, each relativistic jet and its nonrelativistic equivalent do have similar ages, if expressed in the appropriate dynamical time units.

Three-dimensional simulations have clearly shown that non-axisymmetric instabilities will become important if even small perturbations are applied (e.g., Hooda & Wiita 1998). Nonetheless, the HD jets can propagate to very substantial distances without completely breaking up if they have high enough Mach numbers. A careful comparison of numerical simulations and normal mode analysis for relativistic 3-D jets has shown that a wide variety of helical modes can be generated; these imply that dramatic variations in Doppler boosting are possible without much overall bending of the jet (Hardee 2000). Higher resolution simulations of relativistic jets indicate that the instabilities are greatly reduced in comparison to nonrelativistic situations (Aloy et al. 1999). Other relativistic simulations have convincingly shown that the knot structures seen in VLBI observations can be reasonably reproduced in terms of shocks within those jets (e.g., Martí et al. 1995, Mioduszewksi et al. 1997, Gómez et al. 1998).

The collision of a jet with a much denser cloud have recently been reexamined using high resolution 3-D HD simulations (e.g., Higgins et al. 1999, Wang et al. 2000). While powerful jets will destroy most obstructions and weak jets will be stalled and destabilized by them (as probably happens in many Seyfert galaxies), there is a rather small region of parameter space where jets can bend and survive; this could explain some rare ''dog-leg'' morphologies.

The instability of MHD jets, particularly focussed on the question of entrainment, has been carefully studied under various situations recently (Hardee & Rosen 1999, Rosen & Hardee 2000). By precessing the jets at the origin to excite the KH instability, results can be compared with linear stability analyses, and it is concluded that the KH instability is the primary cause for mass entrainment but that expansion of the jet reduces the rate of mass entrainment.

An interesting approach to MHD jet stability has been taken by Frank et al. (2000). The initial conditions for the jets are taken from analytical models for magneto-centrifugal launching and have a more complicated structure than most earlier work. They find new behavior including the separation of an inner jet core from a low density collar. The wavelengths and growth rates from a linear stability analysis are in good accord with 2.5 dimensional numerical simulations (Lery & Frank 2000). For a sub-class of current-driven instabilities in cold supermagnetosonic jets, 3-D MHD simulations have also found good agreement with a linear analysis (Lery et al. 2000). If the initial equilibrium structure has a pitch profile that increases with radius, an internal helical ribbon with a high current density forms, which yields localized dissipation; this might produce particle acceleration within the jet.

5. CONCLUSIONS

Jets are ubiquitous. As astronomical instrumentation has improved we have been able to detect jets over an absolutely phenomenal range of distances and powers. Extremely rapid flows in extragalactic sources explain extraordinarily fast variability, apparent superluminal motions, and the spectra of blazars over 17 decades in frequency. Our viewing of these jets from different angles can explain essentially all of the differences between FR II radio galaxies and radio-loud QSOs as well as the differences between FR I radio galaxies and blazars.

No specific model for the production of cosmic jets is absolutely compelling. While it is highly likely that MHD processes are of importance in the launching and initial collimation of jets, the details of these processes remain extremely controversial. Given the complexity of MHD in full general relativity, this is not surprising. Advances in numerical techniques and computing power are finally allowing tentative explorations of 3-D relativistic MHD flows. However, only when several groups, using different codes and wide ranges of plausible initial conditions, all produce very similar outcomes, will it be fair to claim that the source of jets in AGN is understood.

More confidence can be given to the results on propagating jets, since the results of simulations can be reasonably matched to observations. The idea that deceleration through interaction with the external medium converts FR II type jets into FR I types appears to be valid. Nearly all modern 3-D simulations, whether HD or MHD, whether relativistic or not, tend to produce flows that can propagate over very long distances, though instabilities can yield a ‘‘flailing about’’ of the outer portions of the jet. The interaction of the jet with the external medium always provides a sheath of matter that can assist in confining the jet and appears to be able to slow the growth of unstable modes.

Although we have not had the space to discuss them, we must end by recalling that much smaller and weaker, but still relativistic, outflows that can be legitimately characterized as jets are found in some compact binary systems (Mirabel & Rodríguez 1999). Furthermore, reasonably collimated, albeit much slower, flows are common around young stellar objects (YSOs; for a recent review see Richer et al. 2000). The argument that all of these collimated outflows are formed in very similar ways (e.g., Livio 1999) is intriguing, but by no means convincing. The differences in physical conditions are so immense, and our understanding of the origin of extragalactic jets so tenuous, that any claims along these lines are most speculative. It is at least as likely that a substantially different physical mechanism, such as the X-wind model (Shu et al. 2000) dominates the slow, weak jets in YSOs and differentiates them from cosmic radio jets.

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