Laboratory) reported results on three low-mass systems of known orbital period: 1822-371 (P = 5.57 h), 1916-05 (P = 0.83 h), and 1755-33 (P = 4.4 h). For the first of these, EXOSAT has provided the first complete x-ray light curve, revealing some differences from earlier HEAO-Einstein data. The optical minimum of this system lags behind that in x-rays by 15 min, clearly indicating that the x-ray and optical sources in this system are distinct. The dips observed in the x-ray light curve of 1755-33 show considerable structure on short time scales. Although these dips represent a loss of up to 40% of the x-ray flux, the energy spectrum does not appear significantly altered. The bright x-ray sources at the centers of all three of these objects serve as potential probes of their accretion disk structure, but there are likely to exist substantial differences due to x-ray heating in that structure, in comparison with CV's.

The proceedings were closed with a short summary of the workshop and outline of future directions in CV research by P. P. Eggleton (Cambridge). In his inimitable (save by J. Faulkner) style, he revealed the full extent of our ignorance of these systems, and brought matters to a fitting conclusion.

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Green Bank Workshop on the Physics of Energy Transport in Extragalactic Radio Sources

One astronomical phenomenon that has been receiving a great deal of attention recently is the outward collimated fluid flow in radio jets. Thanks primarily to the high sensitivity and great dynamic range of newer radio telescopes such as the Very Large Array (VLA), these jets are being discovered in great numbers in extragalactic sources and are occasionaly detected on much smaller scales in our own galaxy. Along with the observations of these radio jets, which have been coming thick and fast, our theoretical understanding of them has also been advancing, if not quite as rapidly.

Such activity naturally generates topical meetings. At the IAU Symposium No. 97[1] held in 1981 a great deal of attention was paid to extragalactic jets. Several meetings solely devoted to the topic have occurred since, with the one at Torino in 1982 yielding an excellent volume of proceedings.[2] From 30 July to 3 August 1984, one of an occasional series of informal workshops at the National Radio Astronomy Observatory at Green Bank, West Virginia, was devoted to the Physics of Energy Transport in Extragalactic Radio Sources. Although the title of the conference did not mention the word "jets," their properties and possible explanations were at the top of everyone's agenda.

This was one workshop worthy of that name, since, thanks to the limited space at Green Bank, the number of participants had to be restricted to about 30. The small attendance, along with the sharing of housing and meal facilities, guaranteed a high level of interaction

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among those at the workshop, and spawned new collaborative efforts. Such efforts were facilitated by the request of the organizers, Alan Bridle (NRAO) and Jean Eilek (New Mexico Institute of Mining and Technology), that participants circulate preprints before the meeting.

The format of the workshop was informal, with a mixture of reviews and contributed oral papers presented in the mornings. On most afternoons additional presentations were made and smaller groups held working meetings on particular topics. A great deal of lively discussion punctuated the meeting, usually causing some talks scheduled for the morning to be postponed until the afternoon. Despite the attractions of the televised Olympic Games, the majority of the participants devoted the bulk of their evenings to properly lubricated scientific conversations.

Several fundamental points about radio jets emerged quite clearly from this workshop. The first is their ubiquity; many observers are picking up jets that were previously undetectable, and improvements in sensitivity and dynamic range should only increase the number of detections among many types of radio sources. Second, these jets definitely exhibit a wide range of physical properties, with some almost certainly containing plasma moving at relativistic velocities, while others appear to be turbulent and subsonic. Nonetheless, it is still depressingly difficult to accurately measure many of the jets' most important aspects, such as the temperature, density and velocity of the plasma flowing in them. I will close this introduction by mentioning a positive trend: the numerical modeling of astrophysical jets has been making a great deal of progress, and this trend should continue. A comparison of observations and numerical experiments, leavened with theoretical insight, should allow convincing models of individual jets to emerge within the next few years.

The proceedings of the workshop are being published,[3] and brief versions of most of the presented papers and far more extensive references to the literature can be found there. While this summary will touch on the majority of the work that was presented, the stress naturally reflects personal interests.

SYSTEMATIC PROPERTIES OF RADIO JETS

In reviewing the systematics of current jet observations, A. Bridle noted that there were many differences between relatively powerful sources (defined as $P_{tot} > 10^{25}$ W/Hz at 1.4 GHz) and the relatively weaker ones. For instance: weaker sources often have two-sided jets, while stronger ones seem to be only one sided; in weaker sources the inferred magnetic field direction tends to be perpendicular to the length of the jets, while in the stronger sources **B** is usually along the jets; the spreading rate is larger in weaker sources, yielding wider jets; while weaker jets could be thermally confined by the surrounding medium, parts of many stronger jets almost certainly are not, as indicated by x-ray measurements. Jet structure on the pc scale often mimics that of the multi-kpc scale. For weak sources the relative alignment is generally excellent (within 10°) while for strong sources larger deviations are more frequent. Hot spot structure also varies, with the stronger sources usually exhibiting compact (< 1 kpc), edge-brightened hot spots, while weaker ones rarely exhibit recognizable compact hot spot structure and are usually edge darkened. A recent detailed review of these properties is in Ref. 4.

A very important question is: what types of radio sources contain jets? When weak radio sources were examined, over 80% of them were found to house one or two jets, and among the strong radio quasars (3CR sources) 45–70% had jets. However, only $<$ 10% of strong classical radio doubles were found to have jets in earlier surveys.[4] J. Burns presented a sample of 15 classical doubles whose cores accounted for more than 10% of their total flux, and noted that the ratio of observable jets in maps with a dynamic range of $\sim$2000 : 1 was just about 50% in both this group and a comparable QSR sample. Thus it seems that sources with strong cores, whether quasars or not, tend to have jets at least half of the time, while the weak core sources only rarely exhibit them.

Another important result drawn from this and similar surveys is that jets are often very clumpy, especially in higher power sources. Smooth, continuous jets are common in weaker extragalactic sources, but many of the strongest resemble strings of knots or blobs. Yet another very important statistic for the powerful classical doubles is that none discovered to date (with the possible exception of Cygnus A, to be discussed below) show two-sided jets, while dual jets are frequent among less powerful sources. Burns also noted that a rough proportionality between the core power and the jet power may well exist over about five orders of magnitude in P_{core}.

The fact that pc-scale jets are usually one sided, and that powerful large-scale jets are also one sided, demands an explanation, and several have been proposed. The relativistic beaming, or Doppler, hypothesis notes that a rapidly moving jet pointing towards the observer will appear significantly brighter than one pointing away (a counter-jet).[5,6] Another possibility is the alternating side or "flip-flop" hypothesis, which suggests that most central engines only feed one jet at a time, but then, for some reason, switch to feed in the opposite direction; thus only one jet is strong at a given time, but over a long period the rough symmetry observed between lobe powers and distances from the nucleus can be maintained.[7,8] Obscuration by a belt of material in the galactic nucleus could explain some of the asymmetries on the small, nuclear scale[9] but could not do the trick for the largest jets. Finally, irregularities in the surrounding interstellar or intracluster medium (ICM) could certainly explain some asymmetries. If all the above hypotheses can be ruled out, we would be left with the conclusion that some asymmetry intrinsic to the central engine is necessary.

In order to investigate the Doppler hypothesis, one must know the velocity of the heads of the jets. For this and other obvious reasons, the physical properties of the material flowing in the jets, particularly its velocity, must be determined. Unfortunately, as A. Bridle noted, despite all the indirect evidence for flows in radio jets, there is no hard evidence for a particular jet outflow speed in any extragalactic source. Such strong evidence could only emerge from Doppler shifted lines, as seen in SS 433; but the few lines that have been detected in extragalactic sources, e.g., in Cen A, are almost certainly due to plasma outside the jets. Thus, such line velocities can give some information on the important question of the interaction between jets and the ambient medium through which they flow, but can probably only yield uncertain lower limits on internal flow velocities.

Thus it is not surprising that many of the papers presented at the workshop addressed the question of jet velocities. A study of eight of the largest QSRs reported by J. Wardle showed that all of the seven whose jets were detected were one sided. If such very large apparent size sources were randomly oriented, they should all be within $\sim 15°$ of the plane of the sky, and the Doppler hypothesis could not explain the lack of observed counter-jets, even if the jet velocities are ultrarelativistic. Another study, by F. Owen, of some of the very largest sources, those at the upper envelope of the angular size vs. red-shift diagram, came to the same conclusion.

D. DeYoung gave a review that discussed all of the various types

of velocity indicators and summarized the evidence for and against relativistic motion. Although there are no available direct velocity indicators, and the previously mentioned emission lines from nearby gas are only a semidirect indicator, there do exist several indirect ways that are used to estimate jet flow. Jet morphology, the change of angular size with time in the case of some nuclear jets (the so-called "superluminal" sources), brightness distributions, spectral index changes, polarization data, and x-ray observations have all been used to argue for one type of velocity or another. The idea that relativistic motion occurs in jets is supported by the following facts: relativistic beams are more efficient, in that less energy is wasted in getting out to the lobes; many sources are one sided; small scale jets detected by VLBI are on the same side as the multi-kpc jet; very rapid luminosity changes are sometimes observed; and superluminal motion is detected in some sources. However, another set of observations seems to be inconsistent with relativistic motion. In particular: many jets flare out into relaxed plumes; as mentioned in the previous paragraph, the largest sources, presumably near the plane of the sky, are one sided; many small VLBI jets appear twisted; and many jets seem to fade out between $\sim$10 pc and $\sim$100–1000 pc.

The systematics of energy transport into hot spots was discussed by J. Dreher. The observed power of strong double radio sources, together with the assumptions that the hot spots serve as the termination of the beams, and that approximate equipartition between the magnetic energy and that of relativistic particles exists, implies velocities that are at least mildly relativistic. Ratios of $v_j/c > 0.2$ are needed for all five sources for which there is enough data to perform this analysis, with v_j at least $0.9c$ for Cygnus A. There is some evidence that v/c may increase as the power of the source rises, and this argument also implies that the efficiency at which ultrarelativistic electrons are accelerated in hot spots is at least 10%.

A survey of high power hot spots was presented by R. Laing, who noted that they usually contained a compact component between 100 and 1000 pc in size. They are usually recessed from the leading edge of the lobe, indicating that they may be off to the side of the lobe. Whenever a jet could be traced all the way out, it was found to point to the more compact hot spot, although it must be stressed that not all jets terminate in compact hot spots. Even where the jet cannot be followed all the way from the core to the hot spot, the compact hot spot is always on the same side as any jet or inner knot. The diffuse secondary components are probably not just remnants of the jets after they have turned off, since the morphology, spectral index and magnetic field configuration do not fit that hypothesis.

Although more attention was paid to strong double radio sources and quasars than to weaker sources at this workshop, a great deal of information can be obtained by examining the bent jets that are seen in weaker sources. If the jets are dramatically bent as, or before, they leave the parent galaxy, they are referred to as narrow angle tails, or NATs; if the bending is not as extreme, they are usually called wide angle tails, or WATs.

C. O'Dea showed how the bending in NATs could perhaps discriminate between the models that have been proposed to explain their morphologies. This is because the trajectory constrains the momentum flux down the jet, and the radio emission observed from the tails constrains the energy flux. He argued that the ram pressure bending model[10] produced more reasonable average values for particle densities, efficiencies and mass loss rates than did models that relied on either static pressure gradients within the ISM or on multiple "plasmons" moving along an evacuated channel in the ISM. Such ram pressure bending implies flow velocities $\sim 10^4$–10^5 km/s.

The structure of WATs and the way radio morphology is affected by the cluster of galaxies in which the source is usually embedded were examined by F. Owen. It is generally expected that the dominant galaxy in a cluster should be moving less rapidly with respect to the background medium than other cluster galaxies. Thus ram pressure appears as a natural explanation for the bending of jets from non-dominant galaxies. However, several WATs came from dominant galaxies with huge halos and in some cases the bending is surprisingly sharp. Such galaxies should not be moving rapidly enough for ram pressure to produce jet curvature. Owen also described a remarkable source, 3C 75, in the cluster A400: this galaxy has two nuclei separated by ~ 10 kpc, each of which emits two-sided jets. On one side of the galaxy the two jets emerge in roughly the same direction and then relax into diffuse lobes; but on the opposite side the two jets appear to either coalesce or wind around each other! While no complete explanation of this behavior has yet been put forward, it may be easier to explain the bending of WATs if the bulk of the emitted energy does not originate with the jet kinetic energy, but rather with the turbulence of the ICM with which the jets interact.

P. Wilkinson stressed that sharp apparent bends in jets are not

confined to the 10^4 pc scale, but that many sources, particularly steep spectrum core sources, show abrupt bends between 100 and 1000 pc from the central source. VLBI measurements often show such changes on even smaller scales. In several such steep spectrum core sources, such as 3C 309.1, extremely sharp bends are observed, indicating that we may be seeing a jet rebound from the equivalent of a brick wall. The fact that several of this type of source show similar connections between radio morphology and extended emission line clouds may eventually allow measurements of the jet velocity to be made. Space telescope maps and VLA maps with polarization could provide direct measurements of component motion.

Polarization measurements have often been used to estimate magnetic field orientations. In conjuction with Faraday rotation and depolarization measurements, they have also been employed to measure both relativistic electron densities and the densities of entrained obscuring matter; but R. Laing stressed that such interpretations are frought with uncertainties. For example, unresolved foreground material yields depolarization without Faraday rotation, while a mixture of thermal and relativistic foreground plasma can produce very strong Faraday rotation along with depolarization. Also, while the net field direction is usually taken to indicate a large scale magnetic field within the jet, the same high percentage polarization could come from fields including many small scale reversals.

NEW OBSERVATIONS OF INDIVIDUAL SOURCES

Near the beginning of the workshop C. Walker exhibited an extremely impressive map of 3C 120 that set a new standard for resolution and dynamic range. This result required combining VLBI measurements with VLA maps to illustrate a continuous link between a superluminal core and lobes at ~ 100 kpc from that core. The VLBI measurements used up to 14 stations to get a dynamic range of 800 : 1 for coverage from a few milliarcseconds (mas) out to 250 mas from the core. VLA measurements using a 100 mas beam and sufficient exposure and signal processing to obtain a dyanamic range of 30,000 : 1 were also needed! It is worth noting that the VLBI maps showed that several different blobs have been ejected from the core, at the rate of about one per year; their apparent velocities are all $\sim 1.5c$, but there is weak evidence that they may be accelerating at surprisingly large distances from the core.

One other superluminal source, 3C 345, was discussed in detail. J. Biretta showed that the several components that have been detected by VLBI are following different paths, and at least one of them is currently on a nonradial, accelerating track. These observations cannot be explained by either ballistic motion or simple precession. If one assumes the flux of the core has been constant, then a relativistic Doppler factor of at least 16 is needed if the relative velocity is constant, and $H_0 = 100$ km/s/Mpc. If $H_0 = 50$ km/s/Mpc, then accelerated motion is required.

Some of the first VLBI polarization measurements ever made were reported by J. Wardle. He showed that while more total flux comes from the central component in 3C 345, most of the polarized flux comes from the innermost ejected blob, and was able to derive many of the physical properites of that region. VLBI polarization measurements of the BL Lac sources AO 135 + 164 and OJ 287 were also presented. While these observations are extremely difficult and time consuming to make, they open a new, and probably very useful, window onto nuclear radio sources. Wardle also showed polarization maps of some WATs. The fact that the polarization is clearly stronger on the outer side of the curved jets of some sources is taken to indicate that real bending, and not a relativistic beaming effect, is responsible for the observed jet curvature. Such measurements seem to imply low jet velocities.

One of the more intriguing jet sources, 3C 449, was the subject of extensive measurements presented by T. Cornwell. This source shows oppositely directed jets with strong wiggles; the jets eventually billow out into relaxed lobes. While previous maps showed gaps near the central engine before the jets appeared, these new maps with higher dynamic range fill in those gaps. The newly recognized inner jet regions are strongly polarized, but the direction of the polarization symmetrically alternates between perpendicular and parallel to the jet axis. These jets also alternate between nearly free expansion and overcollimation. Despite the wealth of information available on this source, no really conclusive values for the density of the flowing material have been determined. However, useful constraints on the velocity have been produced, indicating that it is between ~3000 km/s and ~10,000 km/s.

Recent results on M87 were discussed by F. Owen. He stressed the fact that this source is unique in that the radio, optical and x-ray maps are all available and are all similar. Improved dynamic range has shown that the innermost weak knots are not isolated bodies, but rather enhancements of emission within a filled jet. The brightest knot is quite asymmetrical, with an apparent discontinuity on the source-facing side that strongly suggests an oblique shock; this interpretation is also supported by new polarization measurements. The minimum pressure in the jet so substantially exceeds that of the surrounding gas that oblique shocks would be inadequate to confine it and thus the jet should be nearly free. It is difficult to understand how such a free jet remains illuminated; a plausible model involves velocity variations in a relativistically moving fluid.

The archetypal double radio source is Cygnus A, and the earliest jet models were designed to explain its structure. Yet, until recently, no jet had been seen in this source. J. Dreher described observations of the jet in Cyg A made at two frequencies using hybrid maps at the VLA. Very high dynamic range had to be achieved, but a jet is now clearly seen to enter the lobe and continue into one of the hot spots on one side of the galaxy. This jet has a knotty structure close to the galaxy, and possesses a minimum internal pressure that is hard to confine thermally. There are hints in the most enhanced maps of a counter-jet aimed towards the other lobe, with the integrated intensity in the counter-jet roughly 0.2 that of the main jet. Such a ratio could be explained by Doppler favoritism if $v/c > 0.8$ and the source is about 30° from the plane of the sky. The lobes are also revealed to be quite complex in structure, with many wisps or filaments apparent. Maps of Cyg A hot spots shown by R. Laing at $0''.1$ resolution also show filaments. These observations indicate that the hot spots on one side are fed by a single jet that bends within the lobe, favoring a very light, possibly relativistic jet fluid.

The closest active galaxy, Centaurus A, is another radio source that has been extremely important to us as we try to understand the physics of these objects. High resolution, very high dynamic range (13,000 : 1) maps of Cen A at two VLA frequencies were reported by J. Burns. The inner 700 pc or so of the radio jet are seen to be limb brightened first on one side and then on the other. The following are cited as compelling evidence for transverse shocks in these jets: the above-mentioned morphological asymmetry; the fact that the magnetic field (at 2 cm, anyway) is parallel to the jet major axis; that the spectral index steepens away from the most intense regions; and the rough pressure balance inside and outside the jet.

Yet another galaxy to receive an extremely detailed examination is the tailed radio source in NGC 1265. C. O'Dea showed that the jets are continuous, filling in the gaps that seemed to be present in earlier maps. Maps made at 21 cm show that there is a diffuse cocoon around the jet. The polarization is edge brightened and alternates in direction along both jets. The asymmetric wiggles seen in both jets can be attributed to a helical instability in transonic light beams, but probably cannot be explained by a ballistic model. The great deal of power manifested in the jets probably requires both *in situ* particle acceleration and magnetic field amplification.

In only a few cases is there detectable gas intimately connected with radio jets clearly outside the body of the galaxy. One example of this phenomenon, the quasar PKS 0812 + 02, was discussed by L. Rudnick. Here a hot spot is directly on top of optically emitting plasma, and the emission lines show a velocity some 1200 km/s different from that of the quasar. So far, this optically emitting material is mysterious, for it is not clear if it is thermal or relativistic material, nor if it was carried out with the jet or pre-existed and was merely lit up by the jet's arrival. However, detailed searches for similar situations should soon allow reasonably accurate jet velocity determinations to be obtained.

An examination of this conflicting evidence concerning jet velocities seems to require that we admit a wide range in that parameter. While some jets are certainly relativistic (at least on small scales), others are fairly clearly not moving very fast at all. Complete theoretical models must allow for both possibilities.

THEORETICAL MODELS

Much of the theoretical discussion at the workshop centered around the idea that turbulence may have a very important role to play in astrophysical jets. Until recently, turbulent jets had rarely been considered, but several participants argued that they are probably relevant in many cases. G. Bicknell presented several laboratory experiments that showed that while supersonic jets at first pass through

a series of Mach disk shocks, after about 15 nozzle diameters the flow becomes turbulent and subsonic. He argues that sources such as IC 4296 may undergo such a transition and the jet can then appear to "turn on" at a significant distance from the central source, since particle acceleration would be more efficient in turbulent regions. Previously, the high degrees of polarization often observed in the jets had been used to argue against turbulent jets, but Bicknell claims that high polarization can coexist with $\sim$20% turbulent flow.

There are several general observations involving low luminosity radio jets that are not easily explained if their flows are supersonic and laminar. These sources typically have cone angles of about 20° and their surface brightness declines quite slowly. Turbulent jet models seem naturally to give rise to these properties, as once a jet becomes turbulent it can dissipate enough bulk motion to remain quite bright, and widening at an appropriate rate is also natural under these circumstances. Bicknell reviewed the characteristics of subsonic turbulent flow and showed how an integral approach leads to simple dependencies of surface brightness and magnetic field strength on radius that appear to fit NGC 315 nicely. In this picture, low Mach number jets are turbulent, while high Mach number jets could avoid becoming fully turbulent if the "potential core" of the flow (several nozzle diameters) exceeds the scale height of the confining gas.

Turbulent models were also stressed by R. Henriksen, although he concentrated on different approaches, since it is unclear if large scale eddies drive small scale motions or vice versa. He argued that the Mach number may not be as important as the Reynolds number of the flow, and he showed pictures of laboratory jets that looked beautifully laminar when exposures of $\sim 10^{-2}$ s were used, but were obviously highly turbulent when ultrashort exposures of 5×10^{-7} s were taken. Several self-similar models were shown to alleviate the closure problem that arises when moments of the Navier–Stokes equations are taken in an attempt to compute turbulent flows.

Henriksen also addressed the question of the type of flow set up in the gas around a jet, and showed how the Landau–Squires potential flow solution could be generalized to include a magnetic field parallel to the velocity vector. In such models some of the external gas is partially entrained by the jet, and this sets up large draughts or eddies in the confining gas. This moving gas in turn can help collimate the jet, and such an effect could explain the correlation between stronger sources and narrower jets that seems to be observed.

Another aspect of turbulence was emphasized by D. DeYoung, who reviewed the idea that fully developed turbulence could amplify magnetic fields. Using a fully nonlinear, time-dependent calculation, he showed that magnetic fields could grow, quickly increasing in strength on length scales corresponding to the size of the dominant fluid eddies. Magnetic energy could then slowly cascade to big scales which eventually have more energy. While the efficiency of this process is strongly dependent on the details of the assumed initial conditions such as the kinetic helicity, it could be significant, and this type of investigation does need to be followed up.

J. Eilek also concentrated on turbulence in her review, noting that the probable conditions in radio jets indicated that MHD turbulence as well as high frequency plasma waves and electrostatic wave turbulence had to be considered along with ordinary fluid turbulence. This talk was one of the few given at the workshop that treated the problem of specific particle acceleration mechanisms. One starts with a basic energy source, in most cases the bulk motion of a jet ejected from a mysterious central engine; some of this energy is coupled to local "accelerators," which may involve turbulence and/or shocks. These accelerators in turn transfer energy to radiating electrons at a particular efficiency, and it must be borne in mind that these processed particles will in turn affect the structure and evolution of the source.

Although she discussed the by now standard shock acceleration mechanisms and briefly mentioned MHD turbulent acceleration, Eilek paid most attention to magnetosonic waves and Alfven waves. Her recent work with Henriksen indicates that resonant wave–particle interactions can yield reasonable self-similar solutions using the concept of Lighthill radiation. Eilek argued that lower power jets will develop turbulence that can disrupt the ordered flow and might be seen as flocculent tails, but such jets are not too efficient. Higher powered jets can partially avoid the growth of turbulence, however, and somehow such jets probably have higher efficiencies.

Another aspect of jets that has been studied more in the past few years has to do with the possibility of magnetic confinement. As mentioned above, many sources appear to have an internal pressure much in excess of any external thermal pressure, and, when combined with the strong measured polarization, it is natural to suspect that magnetic fields may have an important dynamical role to play. G. Benford noted that charged jets may well exist, with self-generated azimuthal magnetic fields. Such predominantly external azimuthal fields could assist jet confinement and might explain the helical geometries sometimes exhibited by jets.[11] If opposite currents are sent in opposite directions, then the appropriate equations for the jet plasma are essentially those of magnetohydrodynamics; but, in reality, the return currents would not flow in an infinitesimally thin layer at the edge of the beam, so finite conductivity, and thus a finite skin depth, must be taken into account. Burns discussed the prospects for performing laboratory experiments involving current-carrying beams that might scale up in such a way as to shed light on astronomically relevant situations.

The possibility that the polarized, straight, tube-like feature seen emerging from the Crab nebula is due to a magnetic jet emanating from the pulsar magnetosphere was also raised by Benford. This hypothesis is more easily tested than those involving extragalactic sources, and if it holds up, the idea of current-carrying jets will become more popular. It should be noted that the possibly entwined nature of one of the pairs of jets in 3C 75 might be explained if they were carrying currents. Benford also suggested that the need for confinement would be obviated if internal pressures were not as high as has been assumed, and this would be the case if the observed radiation were produced by coherent plasma emission, a mechanism more efficient than synchrotron emission.

An extremely original and exciting new way of considering magnetic effects in jets was put forward by A. Königl. He claimed that magnetic pressure ought to dominate in jets if there is no net current, and that radio knots could represent the synchrotron emission pattern in a nonaxisymmetric magnetic field, not actual compressions in the fluid. In this picture, even though the jet velocity is much greater than the Alfvenic velocity, the magnetic field complements the fluid motions, with the bulk (longitudinal) kinetics dominated by the fluid, but the degree of widening (transverse flow) dominated by the magnetic field. The basic approximation used in this scenario is that the field will strive to reach a force-free configuration. A variational principle which minimizes the magnetic energy subject to the constraint that magnetic helicity must be conserved leads to the conclusion that the minimum energy field configuration is generally a linear superposition of only two modes. The $m = 0$ mode carries a net current and is characterized by a purely azimuthal magnetic field, essentially like the standard model discussed above; but the $m = 1$ mode is basically composed of a pair of flux tubes twisted about each other so that the jet carries no net current.

An important point is that the $m = 1$ mode is very often of lower energy than the $m = 0$ mode, and energy could be emitted via the synchrotron process as the field configuration relaxes from the axisymmetric to the twisted mode. This excess energy must be radiated very efficiently. Unlike other models, which use the shear in jets to produce turbulence which in turn yields synchrotron radiation, in this picture one starts with magnetic energy dissipation, probably via reconnection; some of this dissipated energy could then be channeled into turbulence. A very good fit to the constrictions, oscillations, polarization structure and ridge line wiggles of NGC 6251 can be produced using this model, and it deserves to be tested against other sources as equally detailed data becomes available.

Königl has investigated what such force-free models would look like if viewed nearly end on. The polarization positions and the rotations of the polarization angle that are seen in BL Lac objects like OJ 287 and 0727 − 115 can be explained in terms of this scenario; for if a shock moves down a magnetized jet, "lighting up" the different zones as it moves outward, the polarization is likely to rise in steps and the polarization angle changes might also agree with observations.

Another innovative idea was discussed by K. Lind. He noted that previous models of superluminal sources are really oversimplified. One should not merely look at the integrated distribution, since the apparent expansion really could be due to a shock propagating down a jet (cf. the previous paragraph), and not to expansion of blobs or continuous jets. If the fluid speed is different from the pattern speed then different distributions of emitted flux with angle are produced, and Lind showed a wide range of results, indicating that such shock models can readily fit observations. It is important to note that large changes in log N/log S relations can be produced this way, so that such luminosity functions are not good determinants of beam velocity and do not really constrain observed superluminal motion.

The questions of gaps in jets and the extent of symmetry in double sources were also addressed from a theoretical viewpoint. The ratio of fluxes from a bright, knotty region in a jet to a between knot, or gap, region can be crudely estimated to be $S_{knot}/S_{gap} = (P_{ICM}/P_{gal})^{7/4}$, if equipartition is assumed. W. Christiansen argued that one-sided jets were only apparent since they were "loaded" with material that would cause emission, while the jets on the other side were not stopped as quickly and should have more power available. A simple argument from this premise indicates that the lobe on the side away from the visible jet should be further from the central source, but this is not usually observed. However, adiabatic losses could shift this argument so that it would agree with the usual observations. A conclusion drawn from this premise is that jets must fluctuate rather strongly.

L. Rudnick stressed the fact that very few large double sources are extremely symmetric, and that many maps show features that actually look antisymmetric. In these sources lit-up regions on one side are at the same distances as gap regions on the other side, and vice versa. So far statistical tests have not been able to differentiate between preferential avoidance of absolute symmetry, as a "flip-flop" model would require, and just temporally random, oppositely directed emission. Rudnick argued that sources such as 3C 401 contain "disembodied jets," no longer connected to the central engine. Another type of structure that has been seen recently in the radio lobes of Hercules A is structured filaments that look like shells. While some people have interpreted these structures as being due to compressed blobs of plasma, Rudnick notes that they bear a striking resemblance to smoke rings, or shed vortices. He notes that some of the numerical jet models have shown that a substantial amount of material seems to be "peeled-off" near the working surface of the jet; such material could evolve into the observed rings. This idea is intriguing, but will not be easy to develop into a quantitative theory.

Last among the analytical calculations presented at the workshop that will be reviewed here is a discussion of linear stability analyses by P. Hardee. Several groups have performed Fourier decompositions of perturbations upon cylindrical or slab "jet" geometries; the addition of magnetic fields to these calculations does not seem to affect the small perturbations to which they are sensitive. The $n = 0$ mode corresponds to pinching, $n = 1$ to helical twist, $n = 2$ to elliptical distortions of the jet cross section, and $n = 3$ or greater to various fluting instabilities. It can be argued from the observations that the Cygnus A jet is flattening and twisting, thereby perhaps illustrating the $n = 1$ and $n = 2$ modes.

There has been a debate about whether it is better to perform the analysis for temporally growing modes as a function of wave number, or better to examine spatially growing modes as a function of frequency. Hardee argued that these approaches usually yield the same results. Maximum growth rates occur for shorter wavelength (higher n) modes, and the so-called reflection modes usually grow faster than the ordinary modes. The wavelength at which peak growth occurs is always between three and six times the jet radius. Recent refinements in the calculations have allowed for velocity shear at the jet boundary, replacing the old assumption of a sharp velocity discontinuity; the effect of a slowly widening jet on the perturbation growth has also been investigated. Neither of these changes make tremendous differences in the basic results, which are likely to be good description of small amplitude, large scale disturbances. While one may attempt to perform weakly nonlinear calculations in special cases, these linear analyses will probably prove most useful in checking and helping to normalize fully nonlinear numerical computations.

NUMERICAL EXPERIMENTS

The study of radio jets is one of the several areas in astrophysics where an important trend is fairly well developed: detailed numerical calculations, more properly called numerical experiments, are as essential for understanding the problem as are observations and classical theoretical models. Only the introduction of supercomputers, and their ability to handle complex hydrodynamic flows on fine meshes in two dimensions, has allowed us to really test if the basic theories can match the observations in any but the most crude fashion. Several such computations were presented at this workshop, but this concluding section will first mention some less ambitious, but nonetheless interesting, attempts to build models that include aspects of the physics that have not yet been included in the massive hydrodynamics codes run on the supercomputers.

A study of the stability of jets in relatively realistic atmospheres of elliptical galaxies was reported by D. Sumi. Both types of nonstatic atmospheres were considered: if a wind dominates, the atmosphere is essentially isothermal, the pressure decreases monotonically with distance, and the gas density goes roughly as ($\ln r/r^2$) outside of a core radius, while it is nearly constant inside that radius; in a cooling inflow, the temperature decreases toward the center, the pressure

may be inverted, and the density continues to rise as r decreases. The computations assumed pressure equilibrium between an isothermal jet and the confining cloud. For windy atmospheres the jet seems to remain stable, but in a cooling flow the jet's effective Mach number drops as the external temperature rises with radius, and this implies that the jet is disrupted in a rather short time. These calculations seem to agree with the idea that low powered jets can be easily disrupted, while higher powered ones can remain stable.

The boundary between a relativistic plasma ejected from a central engine and a confining isothermal gas cloud was followed under differing assumptions about the structure of the magnetic field. As presented by P. Wiita, these "1½ dimensional" calculations indicated that if the field was completely confined within the relativistic plasma the jet's disruption would be inhibited, but the jet expands more slowly and the collimation is worse in comparison with nonmagnetic jets. The opposite limiting case, where the entire azimuthal field is taken to reside in a sheath around the beam, provides significantly improved collimation as long as the ordered magnetic energy is less than about 10–15% of the total energy in the jet; but if the field energy exceeds this limit, the jet tends to pinch off in the equatorial plane. The general trend of these results essentially confirms earlier analytical work.[11]

Several two-dimensional (2-D) hydrodynamic calculations were run to investigate the way in which external gas could be entrained by a propagating jet. Observational support for the engulfment of external gas can be adduced from the existence of filaments, optically detected knots, and OB stellar associations in Cen A. D. DeYoung noted that most of the external gas seemed to be entrained near the front of the jet, just behind the bow shock. The irregularities generated by Kelvin–Helmholtz instabilities did not seem to be effective in producing entrainment along the sides of the jet. While high Mach number jets are not efficiently decelerated by the confining gas, they do entrain large amounts of gas. Lower speed jets engulf less gas, but this stuff is less digestible and proves more capable of slowing the jet's progress. It has to be stressed that the two-dimensional nature of the code precludes a full study of this phenomenon, but the results are certainly very interesting.

The most sophisticated, fine meshed, 2-D numerical experiments developed to date were discussed by M. Norman. A grid of models of propagating cylindrical jets have been computed, with the two important variables being the ratio of the jet density to the external density and the jet's Mach number. Light, highly supersonic jets are "cocoon dominated," with the fluid that emerged from the jet being swept backwards around the jet. Vortices in the cocoon drive X-shaped strong shocks into the interior of the jet that might explain the ordered, regularly spaced knots seen in some sources. Denser and slower jets remain "naked," with the densest and slowest showing ordinary mode instabilities, while intermediate cases are dominated by the reflection modes. Instabilities grow at Mach numbers that satisfy $M > 2(\rho_j/\rho_{ext})^{0.3}$. In this case the frequencies of the even and odd modes are about the same, and the wavelength of the dominant mode is proportional to the diameter of the jet.

A fundamental question is: how well do these fluid models really describe the bulk properties of extragalactic radio sources? An important step towards answering this query was provided by M. Norman, who demonstrated how pseudoradio maps of hot spots and lobes could be generated from "snapshots" taken from the computations discussed in the previous paragraph. Assumptions necessary to produce such maps include: the jet boundary is sharp at a contact discontinuity; only the jet material, not the compressed external fluid, radiates; and the synchrotron emissivity is proportional to the pressure to some power between 1.5 and 2.0. All of the "snapshots" were generated from a single propagating jet, with $\rho_j/\rho_{ext} = 0.1$, and $M = 6$. Despite this limitation, five of seven observed morphological types of hot spots could be mimicked by considering three different viewing angles of the head of that particular numerical jet at six different times.

In conclusion, it can be fairly stated that a great deal of progress in both observing and understanding astrophysical jets is taking place. Much of that progress was summarized at the Green Bank Workshop, where the beautiful long exposure maps with extraordinary dynamic range could be investigated in light of an improved comprehension of turbulent flows and compared with detailed numerical models. This progress should continue apace, as more sources are examined more closely, as theoretical models are pushed harder and as the next generation of supercomputers allows 2-D magnetohydrodynamic calculations, and eventually 3-D calculations, to be made. One extremely important area that was hardly discussed at this workshop is the nature of the powerhouse that generates these jets in the first place; but progress seems to be occurring on that front as well, and it is not unreasonable to expect a cohesive picture to emerge by the end of the decade.

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