MECHANISMS FOR JETS

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ABSTRACT. The evidence is now compelling that "jets" delineate the channels along which power is supplied from galactic nuclei into extended radio sources - this accumulating evidence, reported by many speakers, has been one of the major themes of this conference. Jets (often apparently one-sided) have been discovered inside many symmetrical double sources. And M87, familiar optically as a "one-sided jet" for over 60 years, is now found to have weak double radio lobes. The VLA has resolved $\sim$ 70 jets in extended sources; there are now many instances where small jet-like structures are found on the VLBI scale; indirect arguments (some of which I'll mention) indicate that there is directed outflow on still smaller scales, and that the primary collimation may occur right down in the central "powerhouse" (scales $\lesssim 10^{15}$cm). The length-scales relevant to jet production and propagation thus span 9 orders of magnitude; the physical processes and conditions may vary widely over this vast range of scales. This paper will deal briefly with two aspects of jet physics: firstly, some direct inferences from radio maps; and, secondly, some possible mechanisms in galactic nuclei that could set up a collimated outflow.

1. PHYSICS OF RESOLVED RADIO JETS

Velocity

The jet velocity in the galactic object SS433 is well-determined (at $\sim$ 80,000 km s^{-1}), but we do not have equally firm estimates for any extragalactic jet. The only two cases where there is optical evidence are DA240 (Burbidge, Smith and Burbidge 1975), where the so-called "jet" may well be an unrelated foreground feature, and Coma A (Miley *et al.* 1981) where the relation between the moving material and the jet speed is somewhat unclear. For the great majority of jets, we must fall back on indirect arguments; but these yield velocity estimates ranging from $\sim$ 300 km s^{-1} right up to $\sim$ c.

Several of the brighter compact radio sources mapped by VLBI display a one-sided core-jet morphology, and in addition show apparent

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superluminal expansion. As discussed in Dr Cohen's paper, this indicates relativistic motion nearly along our line of sight; the apparent one-sidedness could then just stem from Doppler boosting of radiation from the approaching jet over that from the receding counter-jet. I shall not discuss detailed models for superluminal sources; however, it is hard to avoid the conclusion that relativistic outflow and "Doppler favouritism" are part of the story.

It is then a natural extension to interpret the one-sidedness of many extended jets (as described in Dr Bridle's contribution) in terms of Doppler favouritism, and to conclude that relativistic bulk velocities generated in the nucleus persist out to scales of $\gtrsim 10^5$ pc. Very fast jets have the further advantage that they minimise the mass flux required to provide the thrust and energy input into strong double sources such as Cygnus A.

But there are counter-arguments, suggesting that, at least in lower-powered sources, the flow along jets is much slower:

(i) Some one-sided jets show bends. If the bulk flow follows the jet, then the smoothness of the brightness contours around the bend indicates a subrelativistic jet velocity (Pottash and Wardle, 1979; Van Groningen, Miley and Norman, 1980)

(ii) In sources that show a high degree of reflection or inversion symmetry, one can sometimes give a (model-dependent) velocity estimate. For example, if the bending in 3C31 and 3C449 results from acceleration of the parent galaxy in its orbit about a close companion, then the jet velocities in these sources are in the range 300-500 km s^{-1} (Blandford and Icke, 1978).

(iii) In some jets - NGC6251 being the best example - there seems to be some internal Faraday depolarisation. This indicates the presence of thermal material in the jet, and yields an estimate of its density. According to Saunders *et al.* (1981), the energetics of the extended lobes then suggest a speed $v_j \simeq 1.5 \times 10^4$ km s^{-1}. The energy flux (for a given density in the jet) goes as $v_j{}^3$, so a relativistic velocity would demand 10^3 times more energy. The residual uncertainty in this argument comes from doubt about whether the apparent depolarization is really internal to the jet.

If the jets are not relativistic, Doppler shifts will be negligible, and some other explanation is needed for the one-sidedness often observed. Possibilities include:

Flip-flop behaviour. The one-sidedness may be intrinsic: there may be no beam at all on the other side. But then, to give rise to symmetric double radio lobes, beams must have squirted for comparable times in each direction - averaged over the source lifetime. Moreover, the last injection on the now-defunct side must have been recent enough to generate the highest energy electrons still radiating. But when jets are as long as in NGC 6251 the beam must squirt for $\gtrsim 10^6 (v_j/c)^{-1}$ yrs between reversals. It is surprising that this interval should be so long. Only a small range of timescales can be squeezed between the two constraints. There is no obvious physical mechanism that might cause this "flip flop". One possibility might be that the massive power house has been displaced from a precisely central position and is oscillating in the potential well of the galaxy (or its stellar core); timescales of 10^6 - 10^7 yrs could then arise actually.

Asymmetric internal dissipation. There are many strong classical doubles where the beams are not directly seen, but can be inferred to be active. In such sources, presumably the kinetic energy of the beam is transported out to the "hot spots" without there being too much internal dissipation or boundary friction along its path. It is unknown what determines the amount of such dissipation - and, in consequence, the amount of radiation from the beam. All that is required is the conversion of a few percent of the kinetic energy. Perhaps there is some kind of "turbulent transition", which happens to one jet but not to its counterpart on the other side. For instance, the shear across the jet may be larger on one side, due to different conditions near the nucleus, or to effects of the interstellar environment. If the probability of such a transition decreased with increasing jet power, then the apparent correlation of jet properties with radio luminosity could be understood. The fact that the compact jets in NGC 6251, M87 and NGC 315 are on the same side as the extended jets indicates that the asymmetry must be maintained over many scale lengths.

At present, the arguments support relativistic speeds in the superluminal sources, but are evenly balanced for sources like M87 and NGC 315. An interesting test would be to see if the extended lobes are in any way systematically different on the side where there is a jet; if so, this would tell against "Doppler favouritism" as an explanation for one-sided jets.

The Content of Jets

If extended jets are sub-relativistic, and the apparent depolarization is caused internally, the typical mean densities of thermal electrons are $\sim 10^{-2}$ cm^{-3}. Thus, the pressures and densities in extended jets resemble those encountered in our interstellar medium, and conditions could be just as complex. The gas may be concentrated in dense cool clouds where the field is stronger than average, and the magnetic field may have many reversals. When associated optical emission is seen, this could be thermal radiation from clouds in the jet (cf. SS433); alternatively, it could be synchrotron radiation if high-energy electrons are being accelerated in the jet via shock waves, reconnection etc. (cf. M87).

As Dr Bridle has explained, the collimation and confinement of large-scale jets does not seem to fit any simple picture. The cone angle (in, for instance, NGC 315) seems to widen, and then, further out, narrow down again; there may be a transition from pressure confinement to free expansion and back again; there are some jets where the external pressure cannot be high enough to provide confinement, but which cannot be free either. Moreover, the jet fluid is not flowing adiabatically: internal dissipation, or friction at the boundary, must be tapping some of the bulk energy and converting it into relativistic particles - otherwise the outer parts of jets would not be detected at all.

The extended jet in 4C 32.69 poses problems (Pottash and Wardle 1979). Its internal pressure - even the minimum based on assuming equipartition - is too high to be confined by a plausible external medium. On the other hand, there are problems with supposing that it is free: the thrust estimated on this assumption ($\gtrsim \theta^{-2}$ times the internal pressure) is far larger than could be opposed by the ram pressure of the intergalactic medium.

The serious problems with pressure confinement and with free jets motivate one to consider the properties of the magnetic field, and to ask whether magnetic stresses - squeezing by a field wound round the jet - can aid confinement.

Magnetic Confinement

The evolution of the jet's magnetic field not only controls the synchrotron emission and its polarization, but may also have a strong effect on the collimation, confinement and stability. In the absence of resistivity, the magnetic flux in the jet is conserved along the jet trajectory (unless field is entrained from the surroundings), although the field strength may be amplified by internal shear. If there is no velocity gradient across the jet, the longitudinal field, $B_{\parallel}$, scales with the jet diameter as $B_{\parallel} \propto d^{-2}$, while the transverse field $B_{\perp}$, scales as $B_{\perp} \propto d^{-1}$ (for $v_j \simeq$ constant).

However, a transverse velocity gradient of magnitude $\nabla v \gtrsim v_j/r$ acting over any scale within the jet, would create sufficient shear to make the longitudinal field dominate. Spread across the diameter of the jet, this much shear would correspond to a maximum velocity differential of only $\nabla v_j/v_j \gtrsim \theta/2$. If the shear reflects the overall velocity profile of the jet, as determined by a turbulent or viscous boundary layer, then the greatest amplification of parallel field might be expected in a sheath around the jet. (Other speakers have discussed the data on jet polarization.)

The field strengths inferred within both extended and compact radio jets are compatible with having been advected away from the neighbourhood of a central compact object according to the scaling law $B \propto r^{-1}$. If the jet carries a net current, then it can be magnetically self-confined under the tension associated with toroidal field lines (Benford, 1979; Chan and Henrinksen 1980). (The current involved would actually be comparable with the current postulated to flow through the

Crab pulsar.) In an axisymmetric jet, magnetic confinement can be achieved by re-arranging the density profile so that the toroidal field $B_{\perp}$ varies inversely with distance x from the axis. The magnetic stress then varies as x^{-2} and can be reduced to the value of the external pressure. The return current flows at larger radii still, and the stresses associated with it can be negligibly small. This scaling breaks down in the core of the jet, which is compressed to the point where the combination of particle pressure and magnetic pressure due to $B_{\parallel}$ balances the confining stress associated with the surrounding toroidal field. In this way, the pressure in the core of the jet can be substantially larger than that in the external medium.

The field causing the confinement would be basically perpendicular to the jet direction; however, the hypothesis of magnetic confinement is reconcilable with polarization evidence that $B_{\parallel}$ often dominates, because the synchrotron emission may come predominantly from the "core" rather than the confining sheath.

2. THE INNERMOST FEW PARSECS

If the VLBI "maps" of 3C273 and other compact sources ever became as detailed as those we already have from the VLA for large-scale jets, they would probably reveal the same type of complex and inhomogeneous structure. There must be "in situ" particle acceleration in the individual superluminal blobs; the external pressure has the value appropriate to a galactic nucleus (or quasar emission line region), but it may still not be high enough to confine the blobs. Over the next few years, study of variability in VLBI jet structure may yield clues to the physics of larger-scale jets.

Even the milli-arc-second (parsec-scale) jets may be secondary manifestations of a collimation process on a scale orders-of-magnitude smaller still. There are three reasons for attributing the basic collimation to sub-parsec dimensions:

(i) The apparent power output and rapid optical variability of sources such as AO 0235+164 and OJ 287, and the random behaviour of their optical polarization (Angel and Stockman, 1980), indicates relativistic beaming, and this would be on a scale smaller than that probed by VLBI.

(ii) The immediate environment of a massive collapsed object is the most propitious place for generating a high energy-per-particle.

(iii) The long-term stability of the jet axis can be ensured by the Lense-Thirring effect if the collimation occur close enough to a massive spinning relativistic object (Bardeen and Petterson, 1975; Rees, 1978).

Collimation via the well-known twin-exhaust mechanism (Blandford and Rees, 1974) may develop on any scale, and its qualitative features are scale-independent: collimation may occur at a few hundred Schwarzschild radii if the cloud is bound to the central black hole, at tens to hundreds of parsecs if it is bound to the nuclear star cluster, and on scales of kiloparsecs if the cloud is of galactic scale. On these larger scales, the nature of the galactic environment (e.g. elliptical or spiral) may affect what happens (cf. Sparke and Shu, 1980). Phenomena on all scales may play a role in moulding the shapes and determining the emissivity of the observed radio jets. But, for the reasons just mentioned, the primary collimation probably occurs around a massive compact object.

3. JET PRODUCTION NEAR BLACK HOLES

The cloud which confines and collimates the jets must be gravitationally bound in a potential well; but its pressure must be sufficient to prevent it from collapsing into the centre (or into a thin disc if it is rotating). Consequently, the value of (P/ρ) for the cloud material must be of the same order as the gravitational binding energy. For a cloud in a $\sim 1/r$ potential around a massive black hole, where P/ρ may exceed $m_e c^2$, it becomes implausible to suppose that the pressure comes from an electron-ion plasma with $T_i = T_e$: the electrons would then need to be relativistic, and their cooling (via synchrotron and compton processes) would be very rapid. There are two classes of model for a pressure-supported cloud in a relativistically deep potential well:

(i) The cloud may be supported primarily by radiation pressure. The gas temperature can then be lower by the same factor by which radiation pressure exceeds gas pressure. If the cloud is sufficiently dense and opaque, the radiation will acquire a black body spectrum. If radiation pressure provides the primary support, the leakage of energy must correspond to the "Eddington luminosity" $L_E = 4\pi GMcm_p/\sigma_T$ for the central mass.

or: (ii) The cloud may be supported by <u>ion</u> pressure, the electrons being cooled by radiative losses to $\lesssim 1$ Mev. This option is plausible only when the density is low, so that the electron-ion coupling time is long enough to prevent all the ion energy from being drained away during the inflow timescale.

When a rotating cloud of either of these types is established around a massive black hole, a distinctively relativistic feature of the gravitational potential well comes into play. There will be a "funnel" around the rotation axis, bounding a "region of non-stationarity", within which no combination of pressure gradients and centrifugal force can support a stationary axisymmetric flow. All material within the funnel must either have positive energy (in which case it will escape) or else have so little specific angular momentum that it falls freely into the hole. Along the walls of the funnel, which are roughly paraboloidal in shape, the specific angular momentum is nearly constant and equal to the minimum specific angular momentum which can be swallowed by the hole.

Any cloud surrounding a black hole thus has a toroidal shape (with a lower-density funnel "cored out" around the rotation axis). If relativistic plasma is generated near the hole, it therefore may not need to excavate an escape route via the twin-exhaust mechanism, since there is a pre-existing channel (whose walls will however be modified in shape by the pressure of the outflowing beam).

Detailed studies of tori supported by radiation pressure have been carried out by the Warsaw group and their collaborators (Jaroszynski, Abramowicz and Paczynski 1980; Abramowicz, Calvani and Nobile, 1980; and references cited therein). The radiation emerges especially intensely along the rotation axis. This is because centrifugal effects greatly enhance the effective gravity on the walls of the 'funnel' around this axis. Consequently, radiation pressure might preferentially eject jets. However, even though, along the axis, the radiation flux per unit solid angle can be $\sim$ 100 times the Eddington value (Sikora 1981), this is not an efficient mechanism for producing ultra-relativistic jets. This is because the high ambient density of multiply-reflected radiation within the funnel provides a Compton drag which prevents the attainment of relativistic speeds until the material reaches the outer radius of the torus. If the density of the jet becomes too high, its optical depth exceeds unity; the acceleration must then be treated not just in terms of individual test particles, but by regarding the jet as a fluid within which radiation pressure provides a high (P/ρ). Taking this into account, Sikora and Wilson (1981) argue that radiation pressure acceleration can only be efficient in the "fluid" rather than the "test particle" limit.

These radiation-supported tori, which require a "supercritical" fuelling rate, may be appropriate models for the majority of quasars - those with low polarization, weak radio emission, and an optical continuum that appears predominantly thermal - but may be less relevant to those active nuclei whose main output is conspicuously non-thermal (the "blazars").

Ion-Supported Tori

Tori supported by radiation pressure will always emit thermal radiation with luminosity $\sim L_E$. This will typically be in the optical or ultraviolet band. But the observed luminosity of most active galactic nuclei that display jets is much less than L_E for a $10^8 M_\odot$ black hole ($\sim 10^{46}$ erg s^{-1}). $10^8 M_\odot$ is probably the minimum mass which can have produced the large internal energy contents of the extended radio lobes. (This discrepancy is particularly acute in the case of M87 which is argued (Young *et al.* 1978) to have a black hole of mass $M \simeq 3 \times 10^9 M_\odot$ and an observed nuclear luminosity thus only $\sim 3 \times 10^{-5} L_E$.)

At low mass accretion rates, spherical accretion has a low radiative efficiency, because the infalling material is unable to radiate its internal energy on the free-fall time scale. Disk accretion likewise will be inefficient at low accretion rates if the magnetic(?) viscosity is high enough: gas can still get rid of its angular momentum, and swirl inwards towards the hole, in a timescale shorter than the cooling time. A torus can then form which is supported by ions (whose temperature is $\sim$ 100 Mev near the hole), but in which the electrons cool down below $\sim$ 10 Mev. Unless collective effects couple the ions and electrons much more efficiently than Coulomb interactions do, the ions will be unable to cool on the inward drift timescale if $\dot{M}/\dot{M}_{crit} < 50 (v_{infall}/v_{free\ fall})^2$. Even though this torus may itself radiate very little, it can nevertheless anchor a magnetic field part of which threads the hole, thereby allowing electromagnetic torques to tap the hole's spin energy (in the manner outlined by Blandford and Thorne elsewhere in these proceedings). Poynting flux and/or ultrarelativistic particles would then be collimated by the torus into jets. This mechanism is analysed by Rees *et al.* (1981), who propose that the primary power supply for all the most purely non-thermal active nuclei (e.g. M87, strong double sources, highly polarised "blazars", etc.) could be powered by spinning holes enveloped by ion-supported tori. A hole of $10^8 M_\odot$ could store several times 10^{61} ergs of spin energy; even a low value of $\dot{M}$ could maintain a magnetised torus which could gradually extract this energy.

Production of Beams with Lorentz Factor $\gtrsim 5$

The VLBI data imply that, at least in the superluminal sources, the bulk Lorentz factor of the beams, γ_b, is in the range 5 - 10. (As explained earlier, however, the evidence on beam speeds in other objects is ambiguous.) For an electron-proton plasma to attain this energy, each proton must acquire 5 - 10 Gev, which is $\gtrsim$ 20 times the maximum mean energy per particle that can be made available in an accretion process. This is a general difficulty with purely gas-dynamical processes; it suggests that a different process must be invoked. Two possibilities are:

(i) Electromagnetic mechanisms may channel most of the energy of infalling matter or of a spinning hole into a small fraction of the particles, or into a Poynting flux which can accelerate high energy particles in a beam.

or (ii) The beams may be composed of $e^+ - e^-$ plasma rather than containing ions; $\gamma_b \simeq 5$ can then be attained with only $\sim$ 5 Mev rather than $\sim$ 5 Gev per electron. These pairs may be produced by pulsar-type vacuum breakdown processes, or by photon-photon interaction in a compact source of X-rays and γ-rays. Radiation pressure is of course more efficient for an $e^+ - e^-$ plasma than for an electron-ion plasma. Note however that if powerful jets of $e^+ - e^-$ originate at small radii they will annihilate unless γ_b is initially large.

4. INSTABILITIES?

Even if equilibrium flow patterns exist that can give rise to jets, they may be subject to serious instabilities. Given the difficulty of predicting the stability of terrestrial and laboratory fluid flows, one should be cautious about attaching too much weight to stability calculations, when they are applied to the flow of magnetized (possibly relativistic) plasma flowing throuhg a medium of uncertain properties. Kelvin-Helmholtz instabilities can occur anywhere along the beam's path; but even more serious is the possibility that the setting-up of the collimated flow may be completely prevented by Kelvin-Helmholtz and Rayleigh-Taylor instabilities, in the nozzle region.

Recent calculations by Norman *et al.* (1981) find that the twin-exhaust pattern seems stable only if the width of the nozzle is comparable with the scale height - i.e. for a limited range of energy fluxes (the external pressure being given). At too high a flux the flow pattern is disrupted by violent Kelvin-Helmholtz instabilities, while at too low a flux the channel quasi-periodically pinches off, due to Rayleigh-Taylor instability. These calculations are the best we yet have, but they are still based on assuming simple equations of state for each fluid. Furthermore, they use a 2-D code rather than full 3-D hydrodynamics. Thus the "instabilities" are due to ring-shaped protruberances around the flow boundary. Smarr reports elsewhere in these proceedings some calculations of jet propagation and stability carried out using an improved code.

The simulations by Norman, Smarr and their collaborators are an impressive portent of how numerical techniques will soon permit real "experimental" study of the stability of flow patterns. This numerical approach is likely to be more fruitful than linear stability analyses. However, in comparing these simulations with the observations, it is important not to forget that the only datum we have is the distribution of <u>radio surface brightness</u>. Any apparent "blobbiness" in this, implies inhomogeneity in the quantity B^2 x (path length through source) x (density of relevant relativistic electrons). Unless the magnetic field and the relativistic particles are dynamically dominant, such features could merely indicate regions where particle acceleration is concentrated or the field is specially strong, rather than being substantial features in the overall flow.

5. SCALING LAWS: MINI- AND NANO-QUASARS

The radio structure of Sco X1 looks like a miniature version of an extragalactic double source; SS433 involves collimated jets; and jet-like structures are found in some regions of star formation. This prompts the question of whether these resemblances are merely superficial, or whether similar mechanisms for jet production can indeed operate on vastly different scales.

The flow pattern around (or onto) a compact object is basically controlled by two parameters: the ratio L/L_E (which fixes the relative dynamical importance of radiation pressure and gravity) and the ratio $t_{cool}/t_{dynamical}$ (which fixes the temperature when a stationary flow pattern is set up). Suppose we have an object with given values of M and L, where the flow pattern is axisymmetric and characterised by a velocity $\underline{v}(r,\phi)$, ϕ being the angle made with the symmetry axis; we can then inquire about the properties of a scaled-down object with mass $M' = xM$ $(x \ll 1)$. If we scale $L' = xL$, then the miniature version has the same value of L/L_E. The gravitational radius r_g scales as M. If the flow pattern is similar in the miniature version (which is equivalent to requiring similar viscosity parameters) then $\underline{v}'(xr,\phi) = \underline{v}(r,\phi)$, and the dynamical timescales then scale as $t'_{dyn} = xt_{dyn}$. If the objects were fuelled by accretion, and the efficiencies were the same in both cases, then $\dot{M}' = x\dot{M}$. The characteristic densities then scale as $\rho'(xr,\phi) = x^{-1}\rho(r,\phi)$. Now in general $t_{cool} \propto \rho^{-1}$ x (function of T): the ρ^{-1} dependence applies not only to two-body cooling processes, but also to cyclotron-synchrotron cooling if B^2 scales with ρ^{-1}. We then have $t'_{cool} = xt_{cool}$ - in other words, the ratio t_{cool}/t_{dyn} is the same in the "miniature" flow pattern, given that L is scaled with M.

This means that flow patterns with a given value of L/L_E and $\dot{M}/\dot{M}_{crit}$, around black holes of very different mass, would be very similar. (The precise scaling breaks down when optical depth effects are important, but the above argument does have great generality). The apparent analogy between stellar-scale phenomena and active galactic nuclei may indeed reflect an underlying physical similarity. The relevant parameter is $\dot{M}/\dot{M}_{crit}$, and we can make the following schematic comparisons.

	$\dot{M}/\dot{M}_{crit} \gtrsim 1$	$\dot{M}/\dot{M}_{crit} \ll 1$
$M = 10^9\ M_\odot$	Low-polarization "thermal" quasars	"Blazars", M87 (main power perhaps extracted electromagnetically from hole, not deriving from accretion)
$M = 10^6\ M_\odot$	Seyfert nuclei	Galactic centre
$M = (1-10)\ M_\odot$	SS433	Sco X1 "radio stars"? γ-ray sources?

So there may be miniquasars (Seyferts) and nano-quasars (SS433, Sco X1 etc.); the production of jets may be a generic feature of the flow pattern around collapsed objects on all scales.

6. CONCLUSIONS

In summary, I have outlined how collimated jets can be set up close to a central black hole. However, even if the primary collimation is indeed produced in this way, the jets may experience many vicissitudes (dissipation, reconvergence, etc.) before attaining the much larger dimensions where they are observed in the radio band. The large-scale radio structures are influenced by the galactic and extragalactic environment. The energy densities are low, the speeds are probably not relativistic; but even though the physics is not extreme, a detailed understanding of large-scale source morphology may be as challenging and difficult as computational meteorology. It may turn out that the primary energy production is easier to understand: even though it may entail more "extreme" conditions - relativistic flows, black holes, etc. - the crucial processes may be quite symmetric and standardised, and thus more amenable to serious modelling.

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DISCUSSION

LAING: There is evidence that Faraday rotation and depolarization may be caused by gas in front of the sources. This has also been suggested for the sources in which diffuse optical line emission is seen. Estimates of densities and velocities of jets which depend on polarization measurements should therefore be treated with great caution.

REES: It is certainly important to decide whether the depolarization in (e.g.) NGC 6251 comes from (a) small-scale structure in a foreground Faraday screen; (b) entrained gas in a sheath around the jet; or (c) gas pervading the body of the jet. If (a) and (b) could both be excluded, such evidence would point towards sub-relativistic speeds for extended jets.

BURBIDGE: I gather that you believe that relativistic particles can be generated at high efficiency near a supermassive object. Even so the total energies are assumed to be the equipartition values. This implies certain magnetic field strengths. If you do not have a natural way to get them the total energies may be higher. Also, in places where you require reacceleration, e.g., the jet in M87, can you really get this to occur? What I am really hinting at is that the energies required are much greater than equipartition values unless high efficiencies are present at all stages and equipartition arises naturally. Do you believe that these latter arguments are plausible?

REES: Our best estimates of the overall energy requirements come from the extended radio components. One knows in some cases that the jets cannot be too far from equipartition, because there is now evidence on the external confining gas pressure; similarly, one knows that the proton energy cannot overwhelm the electron pressure (c.f., the Crab Nebula, where similar arguments apply). It is true that there is no general reason for expecting equipartition. However, when the flow pattern involves systematic shear, the magnetic stresses tend to build up until they react back on the flows (i.e., the magnetic energy becomes competitive with kinetic energy). The other part of your question refers to the efficiency with which relativistic electrons can be generated. We know that they occur, with an efficiency of at least a few percent, in supernova remnants (probably via shock fronts), even though the velocities involved are only ~ 0.01 c. It is plausible to expect higher efficiencies when the velocities involved are larger (e.g., for "in situ" production in radio lobes, the "knots' of the M87 jet, and the "blobs" in superluminal sources). Near a black hole--where the bulk velocities are ~ c, and powerful electromagnetic effects can be drawn upon--one would expect that the wavelength energy (up to ~ 30% of rest mass) would go mainly into relativistic plasma. This plasma can radiate near the hole; alternatively, its relativistic internal motions may be converted, via adiabatic expansion, into bulk relativistic outflow, and efficiently transformed back into random relativistic motion at remote locations (source components, etc.). For these reasons (and also because beaming can be invoked to bring down the overall luminosity of extreme objects such as AO 0235+164), I honestly do not believe that the "energetics" of active nuclei raise fundamental problems. If the class of model I've discussed is basically wrong, the flows can only be detected when proper detailed calculations have been carried out.