COSMIC JETS

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ABSTRACT

The evidence that active galactic nuclei produce collimated plasma jets is summarised. The strongest radio galaxies are probably energised by relativistic plasma jets generated by spinning black holes interacting with magnetic fields attached to infalling matter. Such objects can produce e^+-e^- plasma, and may be relevant to the acceleration of the highest-energy cosmic ray primaries. Small-scale counterparts of the jet phenomenon within our own galaxy are briefly reviewed.

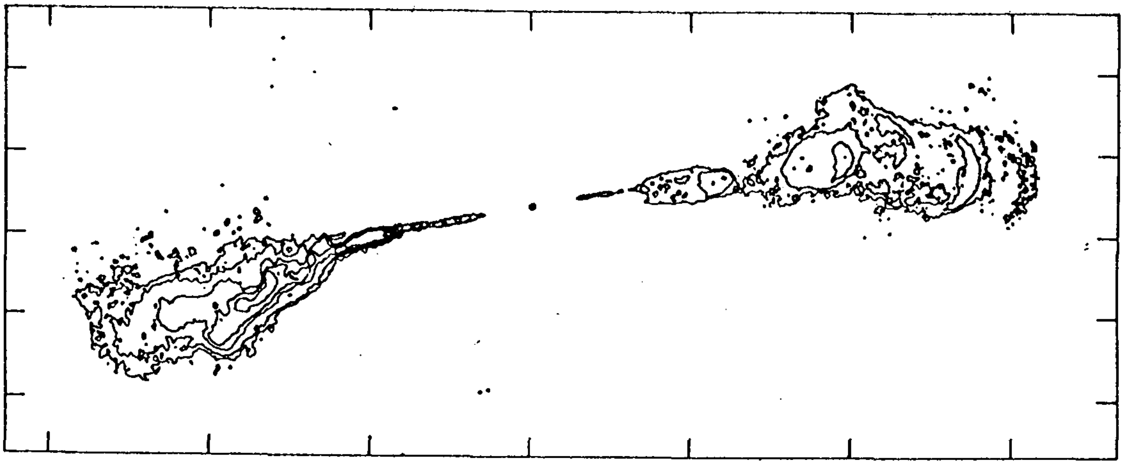
1. INTRODUCTION

The study of extragalactic high energy astrophysics really began just over 30 years ago, when Baade and Minkowski (1954) showed that Cygnus A, the second strongest source in the radio sky, was a remote galaxy with a redshift of 0.05. Radio studies soon confirmed that its emission, along with that from other strong sources, was synchrotron radiation, coming primarily from two blobs symmetrically disposed on either side of the optical galaxy. In the late 1950s Geoffrey Burbidge (1958, and references cited therein) calculated that the minimum energy stored in the radio lobes of such sources in relativistic electrons and magnetic fields was $\sim 10^{60}$ ergs, about the rest mass of a million suns. This was the first indication that some galaxies release non-thermal energy in a coordinated fashion, at a level millions of times surpassing a single supernova.

For many years afterwards, a regular highlight of these conferences was a debate between Professors Burbidge and Ginzburg on intergalactic cosmic rays, and whether cosmic rays pervade the entire universe with the same density as in our galaxy. The issues of cosmic ray confinement, and of how much energy could come from active galaxies, have clarified now; but radio sources are relevant to cosmic ray physics for several reasons: they are the prime candidate for producing whatever intergalactic flux there is; the extended lobes offer, in my view, a vary plausible origin for the highest energy particles we observe; moreover, studies of radio sources yield clues to the nature of acceleration mechanisms in general.

Optical astronomy made its own most crucial contribution to extragalactic high energy astrophysics in 1963, when searches for the optical counterparts of some radio sources led to the discovery of quasars — objects that resembled stars on photographic plates, but whose spectra displayed emission lines with large redshifts (Hazard *et al*. 1963, Schmidt 1963). During the last 21 years, a bewildering body of data gathered in all wavebands has borne out the general concept (adumbrated in the pioneering paper by Burbidge, Burbidge and Sandage (1963)) of 'violent activity' in galactic nuclei. Radio galaxies and quasars are the prime examples of this phenomenon, but the objects known as Seyfert galaxies and "BL Lacs" also involve active galactic nuclei (AGNs).

Optical observations offer a wealth of information on the spectrum, polarization and variability of AGNs. From such data, physical conditions in the emission regions can be inferred. However, it is the radio astronomers who are best able to provide structural information. This is because the radio-emitting regions are often very extended, and also because the angular resolution of radio interferometers with baselines approaching the Earth's diameter surpasses anything optical imaging can yet achieve.

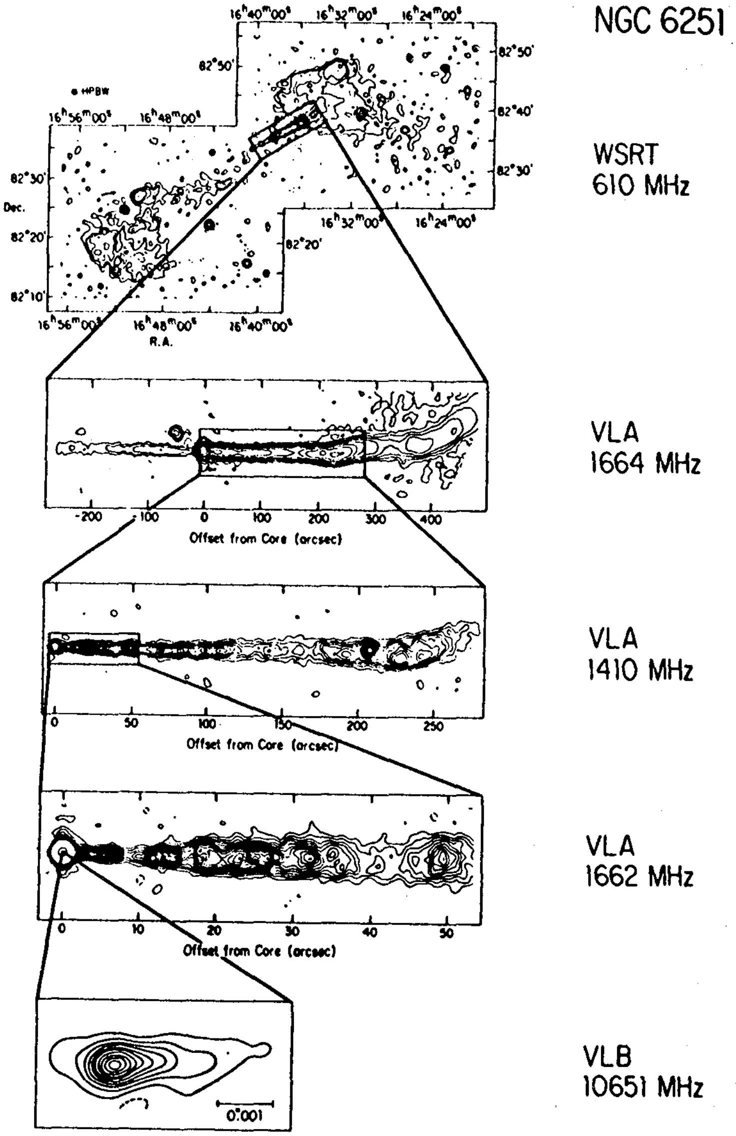


1. VLA map at 5 GHz of the giant double source Hercules A, overall size ∿ 1 Mpc, showing narrow straight "jets" linking the galaxy to the lobes. This high-power source is atypical in showing such conspicuous jets: normally the jets are only as strong as this (relative to the lobes) in sources of lower power. I am grateful to Dr J.H. Dreher for providing this map.

2. EVIDENCE FOR JETS

The reasons why radio sources have their characteristic double morphology, and the nature of the energetic link between the nucleus and the radio lobes, were very perplexing in the early days of radio astronomy. In particular, it was unclear whether the lobes originated in a single colossal explosion, or whether they had been gradually "inflated" by a continuing output of directed energy from the associated galaxy (Rees 1971). These issues have been clarified in the last decade, thanks mainly to the improved resolution and sensitivity of the Very Large Array (VLA) in New Mexico.

Figure 1 shows a VLA map of the double source, Hercules A (3C 348). On earlier maps, nothing could be seen connecting the central optical galaxy with the lobes ∿ 10^6 light years away on either side, but the newer maps reveal conspicuous bridges of radio emission stretching almost all the way from the central galaxy to the lobes. Similar jet-like features are now detected in more than 100 double sources (Bridle and Perley, 1984). Some of the jets are rather inconspicuous: the recently discovered jet in Cygnus A (Perley, Dreher and Cowan, 1984) is barely detected even with the VLA's impressive dynamic range.



2. Montage, adapted from Bridle and Perley (1984), showing the radio source associated with the galaxy NGC 6251 over a wide range of angular scales. The top panel shows the large scale structure: a double source ∿ 2 Mpc in extent. The second panel shows the jet and the (much weaker) counterjet; lower panels show the high-surface-brightness inner parts of the jet at increasing resolution. The large brightness asymmetry between jet and counterjet, and the straightness of the jet, are characteristic of moderately high-power radio sources. The bottom panel, obtained with milli-arc-second resolution via the VLBI technique, shows that the jet emanates from a "nozzle" < 1 pc in scale at the galactic nucleus. The primary power supply probably comes from a region ∿ 5 powers of ten smaller still.

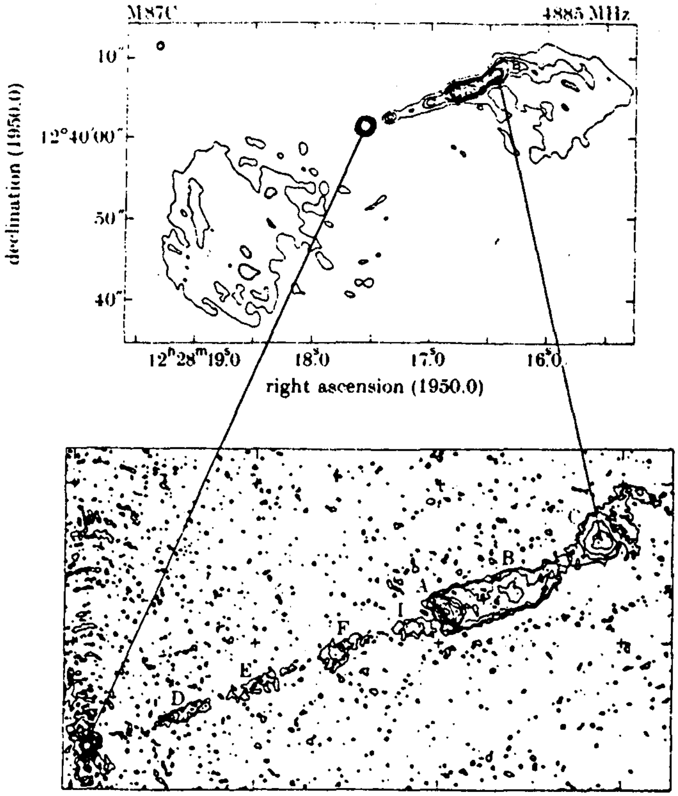
The smallest angular scales resolvable by the VLA (0.1 arc second) correspond to linear dimensions as large as several hundred parsecs in a remote extragalactic source; for finer resolution we must resort to Very Long Baseline Interferometry (VLBI). The montage of NGC 6251 (Figure 2) is specially interesting in showing direct continuity between a plasma 'blowtorch' one parsec long and the large-scale jets and giant radio structure. A common characteristic of jets in strong double sources is that they are asymmetrical: they are detected on only one side; or, if there is a counterjet, it is generally much fainter (by a factor of about 60:1 in NGC 6251 shown in Figure 2).

The jets seem to be conduits along which energy and momentum flow into the extended lobes. But the VLA maps offer no direct evidence for motion. VLBI maps, however, sometimes show dramatic evidence of this: there are several instances where blobs appear to move across the sky, in a direction away from the AGN itself, at 5-10 times the speed of light. There is nothing paradoxical about these 'superluminal' apparent velocities; they can arise from plasma moving at close to the speed of light in directions making a small angle with the line of sight. Motion with a bulk Lorentz factor γ_b ($\gg 1$) at an angle $\sim \gamma_b^{-1}$ to the line of sight yields an apparent transverse velocity $\sim \gamma_b c$. Moreover, the apparent intensity of material moving in these special directions (nearly towards us) is greatly enhanced by the Doppler effect and by aberration. Although detailed models for "superluminal" sources are still controversial, there is thus no obvious improbability in postulating that most of the compact sources in a survey down to a given apparent intensity have this special orientation. Not only, therefore, do the jets contain radiating electrons with high individual Lorentz factors, but the entire medium (electrons, protons (or positrons) and magnetic field) sometimes has a bulk Lorentz factor $\gamma_b > 5$.

The one-sidedness of the large-scale jets in powerful double sources could arise from Doppler favouritism; there would be jets on both sides, flowing in opposite directions, and unless the motion were exactly transverse to our line of sight, one side (the approaching side) would appear enhanced. The famous jet in the Virgo cluster elliptical galaxy M87 could be a relativistic phenomenon, the counterjet perhaps being suppressed by the Doppler effect. This jet, discovered by Curtis at the Lick Observatory in 1918, reminds us that it was actually the optical astronomers who first detected this phenomenon; VLA radio maps (Figure 3) show that M87 has weak double radio lobes plus a one-sided radio jet (whose brightest features coincide with the "knots" in the optical jet). The M87 jet has also been detected in X-rays; its emission in all wavebands is probably synchrotron radiation, produced by electrons accelerated at strong shocks associated with the "knots".

Miniature jets in our own Galaxy

Smaller scale jets are found within our own galaxy. The extraordinary object SS 433 (Margon 1984 and references cited therein) has twin jets with a flow speed of 0.27c (the only jet whose speed is unambiguously known). Recently, directed outflow has been found from some protostars (Bally and Lada 1982, Mundt 1984): these involve much lower energies (and shallower gravitational potential wells), though the collimation may arise from a mechanism analogous to that in the more spectacular extragalactic jets.

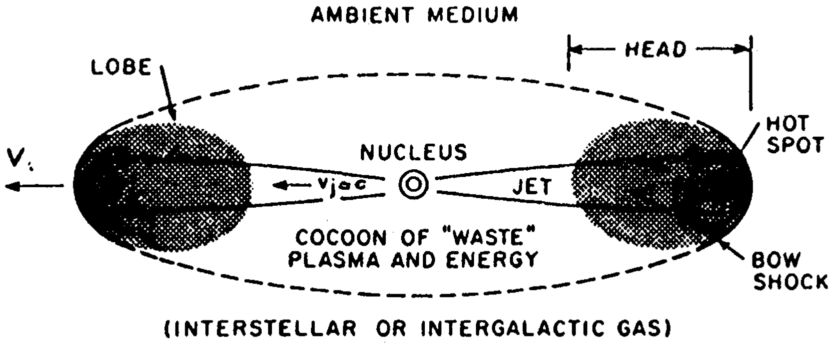


3. Two radio maps of M87. The bottom picture (from Biretta et al. 1983) shows a 15 GHz VLA map of the jet, with 0.12" resolution. The high brightness features correspond with the optical knots (the emission being synchrotron radiation in both bands). The top picture (from Owen et al. 1980) shows a more extended radio view at lower resolution, which reveals that M87 is a miniature double source, with roughly symmetrical lobes ∿ 2 kpc in size and a one-sided jet.

Associated with the galactic X-ray source SCO X-1 are double radio components, resembling a miniature version of an extragalactic double source (Fomalont et al. 1983).

The ICRC conferences are often enlivened by a 'topical diversion', such as the tentative (or even transient) discovery of a monopole, or a quark. This time, we shall undoubtedly hear a great deal about the claimed underground detection of high energy particles triggered from Cygnus X3. Perhaps it is worthwhile, therefore, to recall what radio astronomy tells us about this strange object. It is a variable radio source, with occasional flares lasting a few days. Such flares were well observed in 1972 and in 1982. Limited VLA data, obtained during the 1982 flare, provide just a bit of structural information. The emitting region had a 4:1 axial ratio, thereby perhaps just qualifying as a jet; and expanded at about 0.6 c during the flare (Geldzahler et al. 1984).

The jet phenomenon is ubiquitous. Many different mechanisms may be implicated - the only feature that all jets may have in common is alignment with a rotation axis. In what follows, I shall concentrate on the large-scale jets, emitting synchrotron radiation, which are primarily studied by radio astronomers.



4. Theorists' view of double radio sources (Blandford and Rees 1974): schematic model and "naming of parts".

3. JET PHYSICS

The key elements of a double radio source are: i) a generator of relativistic plasma in the AGN; ii) some bifurcation and collimation mechanism whereby plasma can squirt preferentially in two opposite directions; and iii) a place far away where the relativistic plasma, having ploughed its way through the interstellar medium of the host galaxy out to intergalactic space, is stopped by interaction with the external gas in a shock front (see Figure 4).

The speed of advance V of the "working surface", where the jet is stopped by the external medium, is governed by pressure balance - the balance between the momentum density in the beam and the $\rho_{ext}V^2$ ram pressure force (ρ_{ext} being the density of the surrounding medium). The beam energy is randomized by shocks when it impinges on the external medium; particles here are accelerated and these regions are identified with the "hot spots" in the radio source components. Even if the beams are relativistic (with $V_j \cong c$), V itself is not; we therefore do not expect the same Doppler asymmetry in the lobes and hot spots as in the emission from the jets themselves. The relativistic plasma then accumulates in a cocoon of lower energy density and lower radio emissivity.

We can regard jets as basically fluid phenomena and apply fluid-dynamical analogies. This is because the gyro-radii (even for the synchrotron-emitting particles) and the Debye length are both much less than the jet dimensions, and deviations from charge neutrality are therefore small; also the relative mean velocities of the electrons and ions is small. The MHD approximation is valid: the mean-free path against 2-body collisions is enormous, but the magnetic field, with its small associated gyro-radius, makes the flow fluidlike, as in the solar wind.

The data on jets pose a whole range of questions (all discussed more fully by Begelman, Blandford and Rees, 1984).

Jet speeds

The small-scale superluminal sources certainly indicate outflow at a speed $\sim c$, but it is unclear whether the nuclei of *all* radio sources generate relativistic jets; nor is it clear whether high initial speeds persist over the jets' whole length, or whether frictional effects gradually slow them down. A tenable viewpoint is that jets in the strongest double sources have high Mach number, low internal dissipation, and maintain speeds $\sim c$ out to distances of several hundred kiloparsecs, thereby transporting energy to the extended components in an almost loss-free way. The fact that often only one jet is seen could then arise merely from Doppler favouritism. In lower-luminosity sources (where the jets often appear two-sided, and are more conspicuous relative to the extended lobes) the flow is presumably slower and more dissipative.

What are the jets made of?

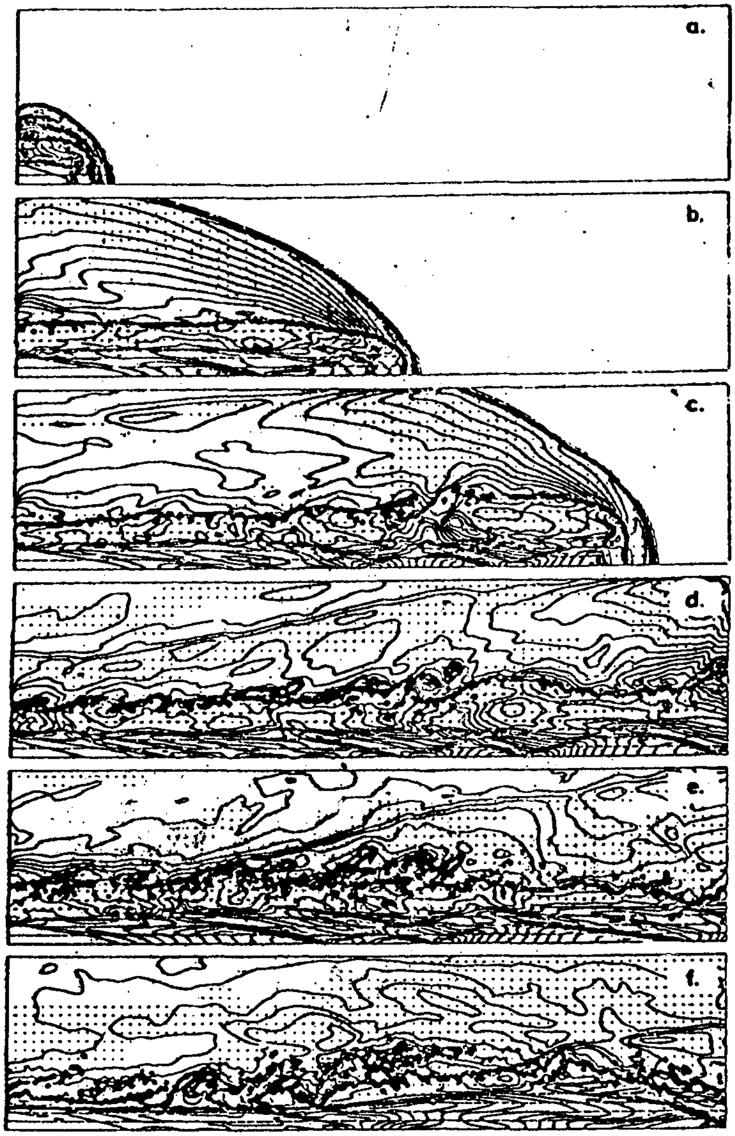
A slow-moving jet would consist predominantly of ordinary swept-up material. However, there are reasons (discussed in section 4) for conjecturing that the 'central engine' generates an e^+-e^- plasma. The kinetic energy requirements of relativistic jets are then somewhat reduced: each electron need be neutralized by just one positron (0.51 Mev of rest mass) rather than a proton (936 Mev).

Confinement?

The flux of energy (and momentum) along the jet can be estimated by considering the dynamics of the lobes and hot spots. The internal pressure within a jet is however lower than the longitudinal momentum flux density by about the square of the Mach number $\mathcal{M}$. The value of $\mathcal{M}$ is often uncertain; a lower limit to the internal pressure (i.e. an upper limit to $\mathcal{M}$) comes from applying the equipartition argument to the radio emission from the jets themselves. This pressure may in some cases be balanced by the pressure of an external medium (e.g. the hot plasma that pervades clusters of galaxies); the latter however is constrained by the amount of X-ray bremsstrahlung, sometimes to values below the minimum inferred pressure within the jet, so we are motivated to seek other agents for confinement. One interesting possibility is that the jets may be confined by magnetic fields coiled around the jet, but the stability of these configurations is still open to question.

Stability?

The observed jets seem amazingly stable against break-up, even in cases (e.g. NGC 1265) where the jet is bent by a "side wind". Clues to why this is so can come from simulations. Aerodynamical experiments may provide valuable insights into purely hydrodynamic aspects of jet physics. They cannot, however, demonstrate the dynamical effects of magnetic fields and relativistic bulk velocity, and only restricted ranges of Mach number, density ratio, and adiabatic index are practicable in the laboratory. Propagation of intense particle beams (or, alternatively, laser beams) into an ambient gas (cf. Bekefi *et al*. 1980)—although the internal



5. Computations by Norman et al. (1982) showing successive stages in the advance of a hypersonic jet into a uniform gas. (These are 2-D simulations, so axisymmetry is artificially enforced.)

dynamics of such beams differ crucially from those in the cosmic-scale beams.— could provide a much higher momentum density and higher Mach numbers than an ordinary gas jet. The interaction with the external medium as such a beam advances may simulate the structure of "hot spots" and cocoons in very strong sources.

The greatest progress will surely come, however, from use of increasingly sophisticated and powerful hydrodynamical codes. These have already (see, for instance, Figure 5) uncovered some gas dynamical properties of supersonic flows that were unanticipated by analytical models and may have counterparts in radio maps (Norman et al. 1983; Williams and Gull 1985). Within a few years, high resolution 3-D computations incorporating electromagnetic effects (MHD) should be feasible. We can then test if it is plausible that jets are confined magnetically, and whether the polarization patterns observed in jets can be explained in terms of the kinematics of expanding shear flows.

Acceleration mechanisms: conversion of bulk kinetic energy into relativistic particles

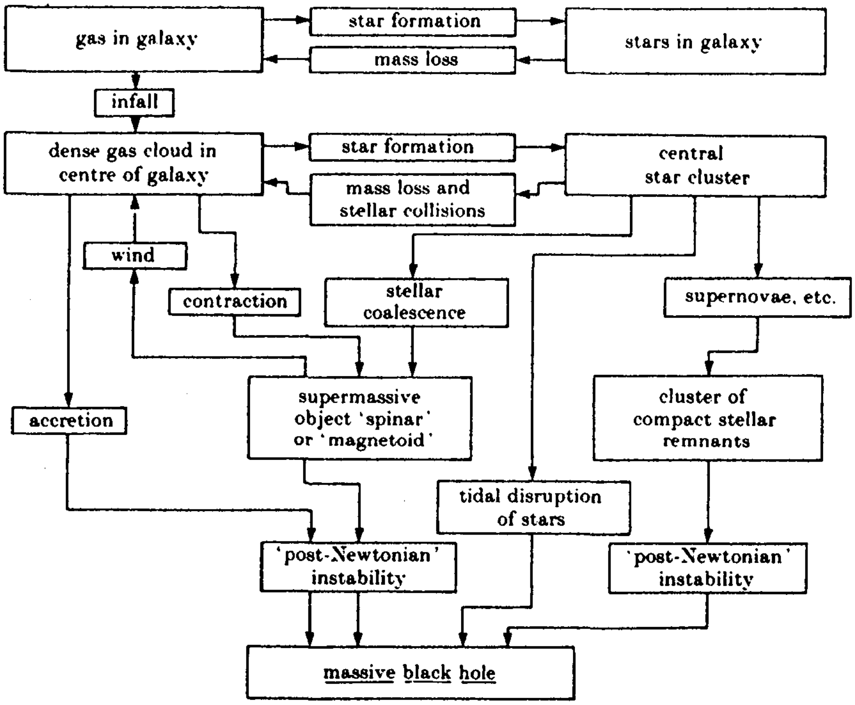
The radiating particles in the radio lobes are presumably accelerated behind the strong shocks that occur where the beam is stopped by external matter. Moreover, *in situ* acceleration is generally required at locations along the jet which emit synchrotron radiation (e.g. the "knot" in the M87 jet shown in Figure 3), and the blobs in superluminal sources are probably associated with internal shocks within a relativistic beam. If these beams emerge from nozzles with scale much smaller than 1 parsec (see section 4) then any initial random relativistic motion would have been degraded by radiative or adiabatic losses.

We know that relativistic particles can readily be accelerated by shocks, even when the shock speed is itself only one or two percent of c (as in supernova remnants). In the present context, the shock speeds are much higher: probably $\sim$ c for internal shocks within the jet; and up to at least ~ 0.1 c in the "bow shock" that advances into the intergalactic medium ahead of the jet and radio lobe. It could even be that the Poynting flux (i.e. the "kinetic energy" of the electromagnetic field) exceeds the kinetic energy of the matter itself. A high efficiency for converting bulk kinetic energy into relativistic particles in radio sources therefore occasions no surprise. The particles whose pressure we can directly infer are, of course, just the electrons (or maybe positrons) responsible for the observed synchrotron radiation. What about protons or heavier ions? It is most unlikely that these dominate electrons by factor as large as 100. Allowance for the associated extra internal energy and pressure would make it much harder to understand the confinement of the high-surface-brightness "hot spots" in radio lobes. (A well-known analogous argument applied to the Crab Nebula shows that the 100:1 ratio does not prevail there either (Trimble and Rees 1970)).

We thus have no direct handle on how many ions are accelerated. However, the large value of B x (length scale) in radio lobes like those of Cygnus A, plus the firm inference that strong shocks occur there, makes them a plausible location for the production of the very highest energy primaries (see, for instance, Cavallo (1978)). On this hypothesis, the $> 10^{18}$ev particles now reaching Earth could have originated in the Southern Hemisphere object Centaurus A. This radio source now has very diffuse extended lobes, and only low-level nuclear activity. But it must, in the (cosmologically) "recent" past have been much more active in order to have inflated and energised the giant lobes - maybe $\sim 10^8$ years ago it was a source whose power rivalled Cygnus A.

The highest energy primaries can be accounted for, without assuming an implausibly flat energy spectrum for a universal cosmic ray energy density of only $\sim 10^{-5}$ eV cm^{-3} (see, for instance, Wolfendale 1984).

This energy density is well below the electromagnetic energy output from AGNs. There is, however, a general constraint on the intergalactic cosmic ray density that could be built up by radio galaxies, pointed out by Rees and Setti (1968): the relativistic electrons in radio lobes would eventually lose most of their energy via inverse Compton scattering of the microwave background, thereby contributing to the cosmic X-ray background. The latter amounts in toto to $\sim 10^{-4}$ ev cm^{-3}, so an intergalactic cosmic ray density higher than this could be ruled out unless the fraction of energy going into electrons rather than ions were correspondingly small.



6. This flow diagram illustrates various runaway processes that could in principle occur in a galactic nucleus, causing an ever-deepening gravitational potential well. A massive black hole is the almost inevitable endpoint; accretion onto black holes, or electromagnetic extraction of their rotational energy, is the most efficient known process that could account for the luminosity of AGNs and the formation of relativistic plasma jets.

4. THE CENTRAL OBJECT IN RADIO GALAXIES

In large radio lobes energy deposited by the jets is dissipated via complex interactions with interstellar and intergalactic media: to model their intricate and environment-dependent morphology are plainly initiated on a scale of $\lesssim 1$ pc. AGNs not only generate a vast "in situ" luminosity (as in the quasars), but sometimes eject energy in these relativistic jets. The jets, however, are just one aspect of the general AGN phenomenon.

The central engines in the most powerful AGNs probably involve black holes of $\sim 10^8\ M_\odot$: arguments for this point of view have been given elsewhere (e.g. Rees (1984)) and I shall not repeat them in the present written text (see, however, Figure 6 and its caption). The characteristic scale of a black hole is the Schwarzschild radius $r_s = 3 \times 10^{13}(M/10^8\ M_\odot)$ cm. Most of the energy release, in all processes involving black holes, happens within a region only a few times larger than r_s. There are therefore several powers of 10 between even the smallest scales probed by VLBI and the dimensions of the primary power source.

Pair production and transrelativistic plasma in compact sources

Before focusing on processes that involve specific (relativistic) features of black holes, it might be worth mentioning some physical processes that occur in *any* sufficiently compact region that emits hard photons.

Suppose that a source of radius r_* emits a luminosity L_γ in the form of Mev photons. These can interact with each other to produce electron-positron pairs, the cross section being of order the Thomson cross section. Most of the photons (each carrying energy $\sim m_e c^2$) will collide with each other before escaping if $n_\gamma \sigma_T r_*$ exceeds unity, where $n_\gamma \approx (L_\gamma / 4\pi m_e c^3\ r_*^2)$ is the photon density. This implies that γ-rays cannot escape freely from any source whose 'compactness parameter' L_γ / r_* exceeds a certain threshold value. The requirement is $L_\gamma > 10(^{m_e}/m_p)\ (^{r_*}/r_s)\ L_{Ed}$, where L_{Ed} is the Eddington luminosity $4\pi GM\ M_p c/\sigma_T$; this inequality is readily fulfilled by non-thermal sources associated with black holes. The primary source would then shroud itself in an optically thick photosphere of e^+-e^- pairs, which would scatter *all* radiation, not just the part with $h\nu > m_e c^2$. Some implications for compact and variable AGNs are discussed by Guilbert, Fabian and Rees (1983). Note that we might expect a broad (0.5 Mev) annihilation line feature in the emission from such objects.

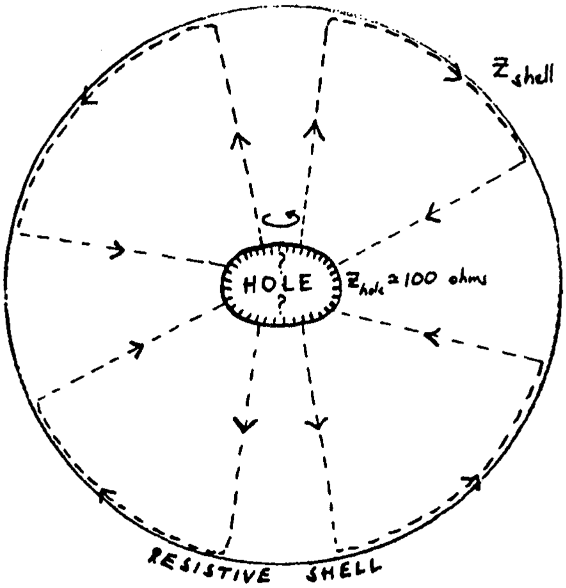
The gravitational binding energy of a proton at distance r from a black hole is $\sim 1000(r/r_s)^{-1}$ Mev. (Except within a few times r_s, general relativistic effects are unimportant, and the potential well is basically just of "$1/r$" form.) For $r \lesssim 10^3 r_s$, gas pressure-supported at (or shock-heated to) the virial temperature would be so hot that electrons would be relativistic if they equilibrated with the ions. The physics of these trans-relativistic thermal plasmas has, until recently, received rather little attention. The electrons tend to be cooler than the ions because 2-body ion-electron coupling is too slow to compete with the radiative cooling losses suffered by the electrons, and because adiabatic compression during infall heats the non-relativistic ions faster than the relativistic electrons ($T_i \propto \rho^{2/3}$ whereas $T_e \propto \rho^{1/3}$). Electron-ion collisions will produce not only bremsstrahlung photons, but also e^+-e^- pairs. (This is an additional source of pairs over and above the $\gamma + \gamma \rightarrow e^+$-$e^-$ process discussed above; the extra pairs will themselves participate in radiative processes). Moreover, even the thermal ions may be energetic enough to undergo nuclear spallation when they collide (Svensson, 1985 and references cited therein).

All the above processes - important not only in AGNs, but also in smaller-scale phenomena such as γ-ray bursts on neutron stars - merit closer attention.

Black holes as "engines"

There is an extensive literature on AGN models powered by accretion onto massive black holes (see Rees (1984), Wiita (1985) for reviews). Such models can, in broad terms, account for the quantity of electromagnetic radiation typically observed. However, one cannot reliably predict the spectrum, nor whether the radiation is thermal or non-thermal: the hardest thing to estimate is what fraction of the power dissipated by viscous friction would go into relativistic particles (via shocks, magnetic reconnection, etc.) rather than being shared among all the particles. Nor do we know how steady or stable the inflow pattern might be. This is a topic where detailed numerical simulations would be worthwhile, particularly if these allowed us to treat unsteady accretion, non-axisymmetric instabilities, and realistic radiative emission and transfer processes.

Despite the lack of quantitative understanding of AGNs in general, the strong radio galaxies (e.g. Cygnus A) have a distinctive property which offers a clue to their central mechanism. The remarkable feature of these particular AGNs is that the "kinetic" power required to energize the extended radio lobes (transmitted by the jets in the form of relativistic particles or Poynting flux) exceeds the radiative luminosity of the nucleus itself. Is there a mechanism that could generate an intense plasma outflow, even if the accretion rate and nuclear luminosity were low?



7. The unipolar inductor mechanism schematically depicted. A magnetic field (not shown) is applied to a spinning black hole surrounded by a much larger non-rotating conducting shell. A current system (dotted lines) is then induced, which dissipates energy in the hole (resistance $Z_{hole} \cong$ 100 ohms), and in the surrounding shell. The power generated in the shell (rather than going to waste down the hole) is maximised, for a given applied magnetic field, when $Z_{shell} = Z_{hole}$.

Electromagnetic energy extraction from spinning holes

There is indeed another possible source of power over and above the gravitational energy released by infalling matter: this is the rotational energy of a spinning black hole, which can in principle be extracted, as was first recognised by Penrose (1969). Astrophysically plausible mechanisms for extracting this energy depend on exploiting the remarkably close analogy between a black hole and an ordinary electric conductor. This analogy is most simply illustrated, for a Schwarzschild hole, by calculating the electric field due to a point charge held at rest near the hole (Hanni and Ruffini 1972). As the charge, with radial coordinate r_c, is moved closer to the Schwarzschild horizon, the field lines get progressively more distorted: they "wrap around" the hole so that as $r_c \rightarrow r_s$ they appear to emanate from $r = 0$, the field being essentially radial for $r - r_s >> r_c - r_s$. It is as though the charge has spread itself over the hole's "surface". For a charge in free fall, the spreading happens in a time $\sim (r_s/c)$. Comparing this with the "classical" estimate of the time $r_s^2/4\pi\sigma$ taken for a charge to spread over a sphere of radius r_s and conductivity σ, we find that the effective resistance of a black hole is of order 100 ohms (cf. Znajek 1978).

A spinning (Kerr) black hole behaves like a spinning conductor (Blandford and Znajek 1977), in the sense that there are constraints on the orientations of any stationary electric and magnetic fields near the horizon. This analogy, spelt out in detail by Macdonald and Suen (1984), is sufficiently close that a "unipolar inductor" mechanism can indeed tap the spin energy of a hole. Specific models for radio sources based on this general concept were developed by Rees *et al*. (1982) and Phinney (1983) and are reviewed in detail by Begelman *et al* (1984).

Figure 7 depicts, very schematically, a unipolar inductor mechanism. For this to operate there must be:

(i) A magnetic field threading the hole (not shown in Figure 7).

(ii) Currents flowing in a circuit into and out of the hole.

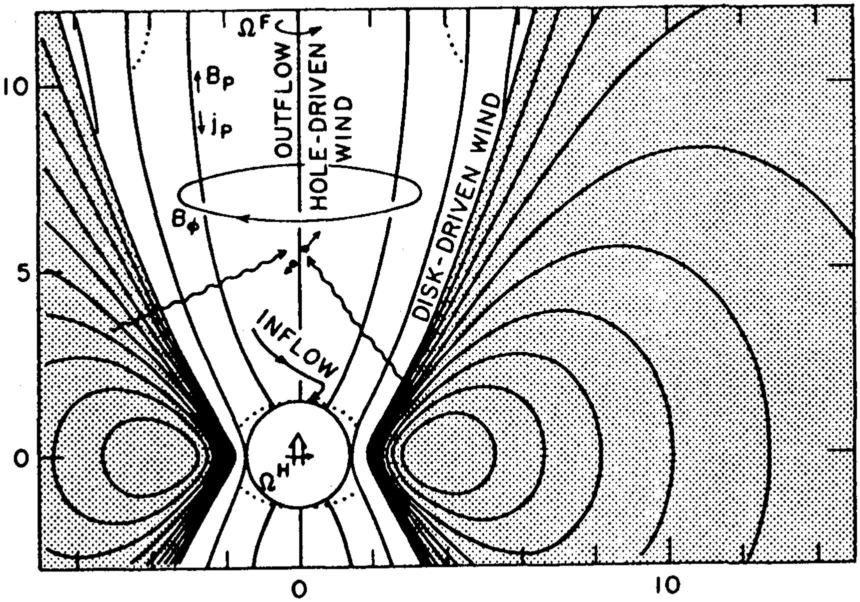
(iii) A near-optimal impedance match, so that the currents dissipate a good fraction of their energy in the outer conducting sphere, rather than in the hole itself.

How can these requirements be fulfilled in a realistic and relevant context?

(i) There must be some conducting plasma near the hole, to carry the currents that maintain a magnetic field; even a very low level of accretion would suffice for this.

(ii) This same low-density plasma can indirectly supply the charges that carry electric current "into" the hole. Dilute plasma near a black hole would radiate inefficiently, and would be at a temperature of > 1 Mev (the virial temperature for $r < 10^3 r_s$ being higher than this). Its low-level radiative emission would then include bremsstrahlung gamma rays. Some of these will interact very close to the hole, yielding a cascade of electron-positron pairs, with more than enough charge density to 'complete the circuit' and carry the necessary current - enough, indeed, to make the magnetosphere essentially charge-neutral, in the sense that $(n^+ + n^-) \gg (n^+ - n^-)$, so that relativistic MHD can be applied.

(iii) The issue of the impedance match and the consequent efficiency, is rather more subtle. Phinney (1983) has explored the physics of the relativistic wind whose source is the pair plasma created by $\gamma + \gamma \rightarrow e^+ - e^-$ in the hole's magnetosphere, and which flows both outward along the funnel, and into the hole. He finds consistent wind solutions in which $\sim \frac{1}{2}$ of the hole's spin energy is transformed into Poynting flux and a relativistic electron-positron outflow.



8. A model for the "central engine" in radio sources. Interaction between a spinning (Kerr) black hole and the magnetic field generates a hydromagnetic wind. External matter (shown stippled) confines a poloidal magnetic field B_p (of strength 10^3 - 10^4 G) threading the hole. (The precise geometry is unimportant; that shown is appropriate for a pressure-supported torus with constant specific angular momentum.) γ-rays (wavy lines) generated in the external matter create pairs in the otherwise empty magnetospheric region from which accreting material is excluded by centrifugal effects. On field lines which cross the event horizon, these pairs carry a current which extracts rotational energy from the hole in the form of a direct-current Poynting flux. (From Begelman et al. 1984).

The general scheme is depicted in Figure 8. Even a low-level and inefficient accretion flow can "anchor" a magnetic field that threads the hole, and thereby tap the hole's spin energy; in these conditions the extracted power naturally goes predominantly into a relativistic bifurcated outflow. The power extracted is of order $B^2 r_s^2 c$ (cf. an "inside out" pulsar light cylinder): for a field $\sim 10^4$G, which can be confined by plasma of density only 10^{-11} g cm^{-3}, this can be $\sim 10^{45}$ erg s^{-1}. This mechanism seems specially appropriate for strong radio galaxies such as Cygnus A (Rees et al. 1982) where the energy flowing along the jets dominates the radiative output of the AGN itself. Electron-positron pairs moving with Lorentz factors ~ 100 would transport some kinetic energy, but most of the power outflow would initially be in the form of Poynting flux associated with the magnetic field coiled round the jet axis, and "frozen in" to the pair plasma. This Poynting flux may be converted into fast particles where the jet encounters ambient material (perhaps on the scale of the VLBI radio components). The expected magnetic field in the jet has the kind of configuration that could cause magnetic confinement and collimation (see Section 3). The plasma around the hole that supplies the currents and anchors the field is just a catalyst: in principle, the power output of a radio galaxy could be sustained with *zero* accretion rate if some of the hole's spin energy were channelled into the surrounding plasma to compensate for its (small) radiative losses.

For the choice of parameters appropriate to strong sources, the maximum available e.m.f. of order $r_g \times B$, may be $\sim 10^{20}$ volts. This suggests that maybe these central regions offer a promising origin for the highest energy cosmic ray primaries. However, just as in pulsar models, the presence of charges "shorts out" the electric field and restricts the potential drop that can be attained. Pair production triggered by γ-rays from the surrounding plasma, amplified by cascade processes that occur if an outflowing wind moves through ambient radiation with a high Lorentz factor, would produce so many charges that, when the energy is shared among them, the resultant bulk flow has a Lorentz factor only $\lesssim 100$. (While shock wave acceleration could still in principle produce a power law spectrum with a tail extending to ultra high energies, the likelihood of photodissociation, etc. makes the compact central parts of AGNs a less promising site for 10^{20} ev particles than the extended lobes.)

The evolutionary context

Radio galaxies may, therefore, harbour massive black holes formed long ago via catastrophic collapse (maybe during a quasar phase of activity). The holes lurked quiescent, the galaxy being swept clean of gas, for billions of years. Then some event, perhaps interaction with a companion, triggered renewed infall - maybe at a low rate but sufficient to reactivate the nucleus by applying a magnetic field. This 'engaged the clutch', tapping the hole's latent spin energy, and converting it into non-thermal directed outflow - Poynting flux and e^+-e^- plasma - which ploughs its way out to scales $\sim 10^{10}$ times larger. If this is indeed what happens in Cygnus A and M87, then these very large-scale manifestations of AGN activity could offer the most direct evidence for inherently relativistic effects.

Massive black holes can generate a high luminosity in two quite distinct ways: straightforwardly by accretion; or via the electromagnetic process just described where the energy comes from the hole itself. The latter process tends to give purely non-thermal power. The properties of an AGN must depend, among other things, on the relative contributions of these two mechanisms, which depend primarily on the accretion rate and the spin of the hole. The properties of AGNs must depend on other parameters - the nuclear mass M, the orientation and properties of the host galaxy etc. Ideally, one would like a unified model which explains the multifarious types of AGN in the same way that our theories for the Hertzsprung-Russell diagram do this for stars.

Conditions around black holes are extreme, but the relevant physics is known, and the key problem is at least well posed: axisymmetric plasma dynamics in a specified gravitational field, the aim being to calculate how much power is derived from accretion, and extracted from the hole's spin, and to find the form in which these respective contributions emerge. Such calculations play the same part in the modelling of AGNs that nuclear physics does in theories of stellar structure and evolution. The evidence that black holes have anything to do with AGNs is circumstantial; but the same is true for other cherished beliefs in astrophysics: the evidence that stars are powered by nuclear energy is also "merely" circumstantial. However the confrontation of models with observations - indirect even for stars - is admittedly much more ambiguous for AGNs: in stars the energy percolates to the observable surface in a relatively steady and well-understood way; in AGNs, on the other hand, it is reprocessed into all parts of the electromagnetic spectrum on scales spanning many powers of ten, in a fashion dependent on poorly-known environmental and geometrical effects within the host galaxy. The massive black hole hypothesis isn't infinitely "elastic", and could be disproved in several ways. It would, for instance, be in serious trouble if very regular periodicities were found in AGNs, or if Space Telescope studies of stellar velocity dispersions places upper limits $<< 10^8 M_\odot$ on the central masses in any radio galaxies with large energy content.

Acknowledgements

Many of the ideas discussed in this paper have evolved in collaborative work with Mitch Begelman, Roger Blandford, Andy Fabian and Sterl Phinney. I am grateful to them, and to many other colleagues for stimulating discussion of many topics that are briefly and inadequately summarized here.

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