NUCLEI OF GALAXIES : THE ORIGIN OF PLASMA BEAMS

Martin J. Rees
Institute of Astronomy
Cambridge, England

The radio structures mapped by aperture-synthesis techniques with the VLA, and discussed earlier at this conference by Fomalont, are energised by activity in galactic nuclei. The compact radio sources resolvable by VLBI techniques (Pauliny-Toth, these proceedings) are on scales $\sim 10^5$ times smaller; but even this still far exceeds the scale where - according to most theoretical ideas - the primary power production is concentrated. This central "core" - involving a large concentrated mass, probably a black hole of $\sim 10^8\ M_\odot$ accreting material from its surroundings - is the primary origin of the power for all categories of activity associated with active galaxies and quasars. In this paper, I shall principally discuss how this "core" could give rise to the fast-moving plasma which emerges in directed beams and energises the radio sources; I shall also comment on some interesting features of radio source structure.

1. THE CENTRAL "CORE"

1.1 Some Characteristic Numbers

In any efficient source powered by inflow into a compact object, the primary power output is concentrated within a region only a few times r_s (the Schwarzschild radius) in size: the r^{-1} fall-off in the depth of the potential well means that the gravitational energy released at much larger r is negligible, though of course radiation or particle fluxes generated at small radii can be reprocessed further out.

The following approximate figures are illustrative of the densities, temperatures, etc. in the primary emitting "core". Suppose that the characteristic dimensions are $\sim 10\ r_s \simeq 3 \times 10^{14}\ M_8$ cm, M_8 being the central mass in units of $10^8\ M_\odot$. The free-fall (or Keplerian) speed throughout this region is $V_{free\ fall} \gtrsim c/3$. The inward drift speed V_{inflow} would be of order $V_{free\ fall}$ for radial accretion; when

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angular momentum is important, V_{inflow} depends on viscosity. Suppose that the accretion rate yields a luminosity L with an efficiency $\varepsilon \simeq 0.1$. Then characteristic quantities are

Optical depth:

$$\tau_e \simeq 1 \times (L/L_E) \; (V_{free\ fall}/\ V_{infall}) \tag{1}$$

Particle density:

$$n \simeq 10^{10} \times (L/L_E) \; (V_{free\ fall}/\ V_{infall}) \; M_8^{-1} \; cm^{-3} \tag{2}$$

The maximum magnetic field, corresponding to equipartition with the bulk kinetic energy, would be

$$B_{eq} \simeq 10^4 \times (L/L_E)^{\frac{1}{2}} \; (V_{free\ fall}/\ V_{infall})^{\frac{1}{2}} \; M_8^{-\frac{1}{2}} \tag{3}$$

The intensity of the radiation field can be expressed by the ratio

$$\left(\frac{\text{Radiation energy density}}{\text{Rest-mass energy density}}\right) \simeq 0.1 \times \left(\frac{V_{free\ fall}}{V_{infall}}\right)^{-1} \tag{4}$$

This implies that the radiation energy may amount to as much as 100 Mev for each particle in the emitting region, a value not approached in other astrophysical contexts apart from pulsar magnetospheres. Another measure of the radiation intensity is the equivalent black body temperature

$$T_{bb} \simeq 3 \times 10^5 \times (L/L_E)^{\frac{1}{4}} \; M_8^{-\frac{1}{4}} \; K. \tag{5}$$

Any thermal radiation emerging directly from the central "core" would tend to be in the far ultraviolet or soft X-ray parts of the spectrum. Another consequence of (5) is that k T_{bb} is far below the "virial temperature" k $T_{virial} \simeq m_p c^2 (r_s/r)$; gas that has cooled down to thermal equilibrium at a temperature $\simeq T_{bb}$ can therefore only be supported against gravity if radiation pressure exceeds gas pressure by a large factor $\sim (T_{virial}/T_{bb})$.

In the central "core", where the bulk velocities are comparable with c, conditions are exceptionally favourable for the acceleration of ultra-relativistic particles. Indeed, the distinction between "thermal" and "non-thermal" particles becomes rather blurred under these extreme conditions. The energy available for each "thermal" ion is $\sim$ 100 Mev, and at kinetic temperatures corresponding to this we cannot assume that the electron temperature (T_e) and the ion temperature (T_i) are equal, nor that there is any well-defined component of the plasma with a Maxwellian velocity distribution. In general, it is likely that $T_e < T_i$, the electrons being efficiently cooled and maintained at energies $\lesssim$ 1 Mev by synchrotron or compton

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emission, except for the small proportion that may have just passed through a shock, or a region of magnetic reconnection, where the coupling between electrons and ions is more efficient than that due to ordinary Coulomb encounters.

Physical processes in "transrelativistic" plasmas where $k T_i > k T_e \simeq m_e c^2$ deserve greater theoretical attention, taking account of magnetic fields, pair production effects, weak electron-ion coupling, etc. Such processes must play an essential role in the "core region" of galactic nuclei: this is the region where the observed non-thermal optical continuum and X-rays are probably emitted, and which indirectly energises all the phenomena occurring further out.

There is always the possibility that a small fraction of the particles can be accelerated in shock fronts, or in regions of magnetic reconnection, to very high Lorentz factors. Cavaliere and Morrison (1980) estimate the maximum energy that can be attained by individual particles. At this maximum energy the effects of the most efficient possible acceleration (a 'linear accelerator' with $E \simeq B$) are cancelled by synchrotron and Compton radiation losses. The maximum γ is that for which the gyroradius ($\propto \gamma B^{-1}$) and radiation length ($\propto \gamma_e^{-1} B^{-2}$) are equal. Of course this is very much an upper limit: on overall energetic grounds it is unattainable unless the available power can all be channelled into a very small favoured fraction of the particles (as may happen in pulsar-type 'light cylinder' mechanisms). If the particle acceleration is limited by radiation reaction, note that it is easier for ions than for electrons to attain very high individual energies.

More precise estimates than (1) - (5) for physical conditions in the central core can be made on the basis of specific models (see, for example, Blandford and Rees 1978a, Maraschi et al. 1979, Rees 1980, Cavaliere and Morrison 1980). The requirement that the electron scattering optical depth be $\lesssim 1$ (since otherwise the high polarization observed in the optical non-thermal continuum would be washed out) implies that the amount of material in the emitting core must be $\lesssim r^2 m_p/\sigma_T$. For $r \lesssim 10^{15}$ cm this implies a mass $\lesssim 10^{-3} M_\odot$: in other words, about ten orders of magnitude less than the likely central mass enclosed within r. This occasions no problem in models involving accretion onto a black hole (since the only material that need actually be present around the hole is that required to supply the power for a time $\sim r/c$); but the requirement that the density in the emitting region is 10 orders of magnitude less than the mean density of matter enclosed within it is a severe constraint on spinar-type models where the bulk of the material is postulated to be still in an un-collapsed state.

1.2 Radiation Mechanisms

The optical polarized continuum is most naturally interpreted as synchrotron radiation. The X-rays could be explained similarly, but could alternatively be comptonised bremsstrahlung from plasma with $T_e \simeq 10^9$ °K. For a fuller discussion of continuum radiation from the core, see O'Dell (1979) or Fabian and Rees (1978).

In discussions of non-thermal emission from galactic nuclei, some authors still allude to the so-called "inverse Compton problem" i.e. that the relativistic particles cannot cross the emitting region in their synchrotron lifetime unless B is supposed so weak that the Compton losses becomes overwhelming. While the optical continuum sources are centainly in this parameter range, this difficulty can be evaded if acceleration occurs in a distributed way or in localities (e.g. regions of field reconnection or shock fronts) dispersed through the volume. No location is more propitious for particle acceleration than the "core" with properties described above, throughout which the bulk velocities are $\gtrsim c/3$ and whose field strengths are higher than in any other astronomical context save degenerate stars. The dispersed acceleration needed to avoid the "inverse compton problem" thus seems inevitable rather than an ad hoc contrivance.

A general constraint in the high-luminosity sources, discussed by Blandford and Rees (1978a) and Cavaliere and Morrison (1980) comes from the condition that the saattering optical depth of the emission region must be $\lesssim 1$, other wise the polarization would be reduced by electron scattering. If each relativistic electron injected into the volume were to cool (in $t_{rad} < r/c$) and thereafter remain for $\gtrsim r/c$, this condition would be violated. The conclusion is that such relat-vistic electrons must be reused several times.

1.3 Coherent Emission?

None of the reliably-detected rediation from galactic nuclei need be coherent. The VLBI radio components studied at $\gtrsim 1$ GHz all lie apparently below the "Compton limit" (Pauliny-Toth, these proceedings); the brightness temperature in the optical and infrared continuum, even if the dimensions are $\sim 10^{14}$ cm, is low enough to be compatible with incoherent synchrotron or Compton emission. At lower radio frequencies (< 1 GHz) variability is now well established in several sources. The inferred brightness temperatures (neglecting relativistic factors) exceed 10^{15} °K, and bulk Lorentz factors as large as ~ 50 may be needed to bring the temperatures below the Compton limit of $\sim 10^{12}$ °K. While this cannot be ruled out, it would be hard to devise a model with plausible efficiency in which the bulk relativistic factor was so large.

The possibility of coherent emission, particularly in the radio band, certainly cannot be ruled out. The field strength in the core being up to $\sim 10^4$ G (cf eqn (3)) the gyrofrequency can be in the GHz band. This field exceeds the estimated value at the light cylinder of pulsars with $\sim$ 1s period: the flow pattern around a black hole in many respects resembles an "inside out" light cylinder (Blandford and Znajek 1977). Thus coherent cyclotron-maser emission cannot be excluded.

But if the radiation is produced deep in the quasar core, it is vulnerable to absorption (the inverse of incoherent emission) at larger radii. Moreover, so high would be the brightness temperature T that induced scattering (which swamps spontaneous scattering by a factor (kT/m_ec^2) x (solid angle factors)) could quench the radiation unless there were directions where $\tau_{es} \ll 1$ or the electrons were all flowing out with high Lorentz factors in which case relativistic corrections reduce the scattering (cf Wilson and Rees 1978). Thus, if the sub-GHz variations involve coherence, it is likely to be a mild degree of coherence within a region comparable in size to the radio components already resolved by VLBI, rather than pulsar-type emission from the central "core".

2. OBSERVATIONS OF BEAMS AND JETS

There is now strong morphological evidence that active galactic nuclei give rise to jet-like features, with lengths ranging from a few parsecs to hundreds of kiloparsecs. Phenomena observed to date include:

a) Jets associated with double radio sources. These jets, observed in NGC 6251, 3C 66B, 3C 219 and NGC 315, are linear features with opening angles in the range of 3-15^o and are often one-sided. So far, jets have only been reported associated with weaker, comparatively close-by radio doubles, but this may in part be a selection effect.

b) Jets associated with compact radio sources, eg 3C 273,3C 345, 3C 147 and 3C 380 (see Readhead, 1979 and references cited therein). Recent results from VLBI have shown that compact variable radio sources are usually of the "core-jet" type in which an inhomogeneous jet emerges from an unresolved optically thick nucleus. Apparent superluminal expansion is often observed between prominent features in the jet and the core. This is interpreted as evidence for relativistic motion within the jets (Blandford *et al*. 1977, Mascher and Scott 1980). Compact jets are usually roughly aligned with larger scale radio features where these exist. However, the jets in the powerful sources are bent through angles of up to 30^o as they are observed with progressively larger angular resolution (Readhead *et al*. 1978). This bending is probably exaggerated because the jet makes a small angle with the line of sight, a condition that can also give rise to superluminal expansion (Scheuer and Readhead 1979, Blandford and Konigl 1979). Extended double radio sources generally contain relatively faint compact central components; the brightest of these (eg 3C 236 and Cygnus A) have also been examined by VLBI and show linear structure. These compact sources are much more closely aligned with the centre radio components, suggesting the absence of a strong projection effect.

c) Optical jets. The most notable optical jets are those associated with M 87 and 3C 273,nuclei in which there is independent evidence of activity. Both of these are also radio jets. Optical emission has also been recently detected from 3C 66 and 3C 31 (Butcher *et al*. 1980). A jet-like feature displaying emission lines blue-shifted by 3000 km s^{-1} has been associated with DA 240, but this bears no relation to the radio structure (Burbidge, Smith and Burbidge 1975).

d) X-ray Jets. Centaurus A has recently been shown to contain an X-ray jet located a few kpc from the nucleus and apparently feeding the inner radio lobes (Schreier et al. 1979). This may be related to the optical jet reported earlier by van den Bergh.

e) Galactic Jets. The moving emission lines from the galactic object SS 433 have been modelled kinematically as a pair of anti-parallel precessing jets (Abell and Margon 1979) with a velocity of $\sim 0.27c$. This is the only case where we actually know the flow speed. There is also evidence for radio jets from SS 433 which may suggest an analogy with Sco X-1.

f) Inferred Directivity on Unresolvably Small Scales. The VLBI data on the "superluminal" compact radio sources suggest that beams exist on scales as small as a few parsecs. This is still several orders of magnitude larger than the compact source from which the power probably derives. There is no real prospect of probing smaller scales by radio techniques. Synchrotron self-absorption suppresses the power from smaller regions; and even if a coherent mechanism operated in some sources earth-based VLBI would have inadequate resolution to resolve them. Indirect evidence for collimation on still smaller scales comes, however, from studies of optical continuum variability. There are some ultraluminous and rapidly variable objects, such as B2 1308+326 and AO 0235+164, whose optical and infrared luminosities would attain values $\sim 10^{49}$ erg s^{-1} if the emission were isotropic. These vary in intensity and polarization on timescales of $\lesssim 1$ week, the degree of polarization being up to $\sim 30\%$. These could be the members of a (more common) population of beamed sources which happen to be pointed almost towards us (Blandford and Rees 1978)). This would obviously ease the energetic problem, as well as the difficulties of accounting for the rapid variability, high polarization, etc. Support for this scheme comes from Angel and Storkman's recent (1980) optical studies of highly polarized and variable objects, which they call "blazars". The most extreme variables (such as the two sources mentioned above) have polarization vectors that vary over all "points of the compass". Contrariwise, the less luminous objects and those associated with extended double radio structure (which would be more nearly transverse to our line of sight) display a preferred long-term polarization orientation.

Compared with a non-relativistic model for a source with a given observed flux and variability timescale, a suitably oriented beam model with bulk Lorentz factor γ_b yields altered estimates for various quantities as follows:

inferred maximum angular size $\propto \gamma_b$;
inferred maximum surface brightness $\propto \gamma_b^{-2}$;
radiation energy density in frame of emitting material $\propto \gamma_b^{-6}$;
overall luminosity of source (integrated over 4π steradians) $\propto \gamma_b^{-2}$.

3. BEAM SPEEDS, AND PHYSICAL CONDITIONS IN BEAM PLASMA

One cautionary comment may be helpful before addressing the physics and collimation of beams:

The beam or jets that concern us in astrophysics are generally neutral. The electrons and the ions (or positrons) which neutralise them have essentially the same density and move with very nearly the same speed. This contrasts with the situation in most laboratory or terrestrial beams (Bekefi et al. 1980). Moreover, for radio source applications gas dynamics is a good first approximation; analogues with hypersonic gas flow (and even wind-tunnel experiments) may prove more helpful in developing our intuition than comparisons with plasma beams. The Debye length of astrophysical beams is vastly smaller than the overall scales involved, except in some extreme models of electrodynamically driven outflow where energy is carried away from a compact object by charges of energies 10^{20} ev (cf Lovelace et al. 1979 and references cited therein). The magnetic field is crucial in making the flow basically fluid-like (cf the solar wind); even though the mean free path for two-particle encounters is very long, the gyro-radius is much smaller than the flow scales. Note however that the pressure may become significantly anisotropic if the magnetic field is dynamically important.

3.1 Indirect Evidence for Beam Speeds in Extended Sources

We observe direct and indirect manifestations of beams on scales much larger than those probed by VLBI, but on these scales (where we of course see no direct evidence of rapid motion), evidence on the jet speed V (not to be confused with the expansion speed of the double radio source) is conflicting. Arguments can be given in favour of values ranging from the escape velocity of an elliptical galaxy ($\sim$ 300 km s^{-1}) to the speed of light. The existence of superluminal expansion suggests that $V \simeq c$, as might be expected if the jets originate at the bottom of a relativistic potential well. However, there is the problem of "waste energy" first emphasized by Longair et al. (1973). In many sources a lower bound on the momentum flowing through the jet can be obtained by multiplying the minimum pressure in the hot spots by their apparent area. Typical values are in the range 10^{34} - 10^{35} dyne. Further multiplications by V/2 gives the jet power L_o. A large value of V often leads to powers much greater than appear to be dissipated as heat in the radio components. If a jet emerges from a collimation region with a speed $\sim$ c and is subsequently decelerated to a speed $V << c$ by entraining surrounding gas, then conservation of linear momentum (approximately valid for a highly supersonic jet) implies that the power in the collimation region exceeds the final power by $\gtrsim (c/V)$. The "waste energy" that is difficult to dissipate invisibly in the radio components has then got to be similarly processed in the nucleus. For a strong source like Cygnus A, a relativistic jet power is 10^{46} erg s^{-1}, much greater than the known power in the nucleus.

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There is the opposite problem with the mass flux. If the jet is decelerated by entrainment of surrounding material, then the mass loss must increase by $\sim$ (c/V). Again, using Cygnus A as an example, a jet speed of only 1000 km s^{-1} requires 100 $M_{\odot}$ yr^{-1}; over the lifetime of the radio source, at least 10^{10} $M_{\odot}$ of gas would have to be injected into the radio components - much more than is believed to be present within an elliptical galaxy. (Most of this mass would in any case have to be hidden in cool, dense filaments in order not to lead to excessive Faraday depolarization.) So high jet speeds seem to require too much energy and low jet speeds too much mass for the galaxy to provide.

The so-called "head-tail sources" such as NGC 1265 can be interpreted as twin-beam sources where the beams are being curved sideways by the transverse pressure due to the motion of the galaxy through the surrounding intracluster medium (Begelman et al. 1979, Jones and Owen 1979). In this picture, the radius of curvature of the beam (for a given transverse force) tells us the momentum discharge; the energy flux along the beam is then V times the momentum discharge. This line of argument favours a value V $\gtrsim 10^4$ km s^{-1}. If the beams in NGC 1265 were actually moving relativistically, the energy flux would be larger than is required to supply the power input into the tail.

In sources where there is evidence for internal Faraday depolarization within the beam, one can infer the plasma density and thereby estimate the beam speed on the basis of either (a) assuming a value for the power carried by the beam, or (b) by assuming (eg in NGC 6251) that the beam is "free", so that V must exceed the internal sound speed by at least θ^{-1}, where θ is the opening angle of the beam.

With improved and more extensive observations, it should be possible to refine all the various methods of estimating V. At the moment, however, it is an open question whether any of the beams observed on scales >> 10 pc are moving relativistically, and there are good arguments against this view for some relatively weak sources. It is still a plausible conjecture, however, that the beams carrying energy out to the components of strong radio doubles have relativistic speeds. For this reason, and also because of the direct evidence for relativistic jets in components probed by VLBI, it is important to investigate how beams can be collimated in galactic nuclei, and whether relativistic velocities can plausibly be attained.

3.2 Why are the Jets Generally "One-Sided"?

One apparent puzzle is the prevalence of one-sided jets even in sources where the extended structure resembles a symmetric double. There are four classes of explanation:

(i) Relativistic flow and "Doppler favouritism". Given the strong evidence for bulk relativistic flow in the variable compact ("superluminal") sources, it is not a great extrapolation to suppose that some larger-scale beams may be moving relativistically - for

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instance, those in M 87 and NGC 6251. If two identical jets are observed, pointing in opposite directions along an axis aligned at θ to our line of sight, the relative observed fluxes would be in the ratio $F = [(1 + V/c \cos \theta)/(1 - V/c \cos\theta)]^{2+\alpha}$. (Note that the exponent is $2 + \alpha$ rather than $3 + \alpha$ because we consider the contribution from a given projected length of it, rather than from the plasma ejected in a given interval: each element on the receding side contributes for longer). If $V \simeq c$ the asymmetry is very marked even when θ is not specially small. For random orientation the median value of θ is 60^o; this yields an asymmetry approaching $3^{2+\alpha}$ if V is close to c. The only really compelling arguments against this model would arise if symmetric jets were never seen in double source. Also, if the depolarization suggests a high internal density, this would be incompatible with a relativistic bulk velocity.

[A variant on this is the hypothesis that the relativistic electrons have an anisotopic distribution, even though the field along which they are gyrating is coupled to material that is not moving relativistically].

(ii) 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 $\gtrsim 10^6 (V/c)^{-1}$ 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.

(iii) 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. Conceivably this 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.

(iv) Intervening absorption. A further possibility, which may contribute to the asymmetry at least for compact jets, is that a central gas cloud or disc may obscure the far side of the nucleus. Free-free absorption would be the main mechanism, and this has the ability to absorb at $\lesssim 5$ GHz if $n_e^2 \ell \gtrsim 3 \times 10^7$(for $T = 10^4$ ^oK). Values of $n_e \gtrsim 10^4$ cm^{-3} can be expected out to 10pc; this is in itself a possibly sufficient explanation for the absence of counterjets on the VLBI scale. Such absorption cannot, however, prevail out to $10^4 - 10^5$ pc; the thermal plasma that can be expected to pervade a whole galaxy is too rarified to cause absorption at GHz frequencies.

3.3 Inversion Symmetry and Precession Effects

Some extended sources display "inversion" (or 180^o rotation) symmetry suggestive of precession in the beams' orientation. (Two good examples are shown in Figure 5 of Fomalont's contribution to these proceedings.) The apparent precession may be a manifestation of complex non-axisymmetric gas flow in the gravitational potential well of an elliptical galaxy. However, if the beams are collimated on a very small scale, near a massive black hole, changes in the hole's spin axis must be involved in the phenomenon.

One possibility (Rees 1978a) is that a hole whose spin axis is misaligned with the angular momentum vector of infalling gas is gradually (on a timescale $\sim M/\dot{M}$) being swung into alignment. The only way a black hole can actually <u>precess</u> at a significant rate would be if it were orbited by another hole of comparable mass. Massive black hole binaries would form if two galaxies, each containing a black hole in its nucleus, were to merge. Mergers between galaxies appear to be frequent. cD galaxies in clusters and small groups were quite probably formed in this manner and there is strong evidence that the nearby active galaxy Centaurus A is a merger product (Tubbs 1980). If massive black holes are present in their nuclei--relics of earlier activity--then they will settle, under dynamical friction, in the core of a merged stellar system. Many cD galaxies contain double or multiple cores that may have formed in this way. There are other scenarios for binary black hole formation. For instance, a rotating supermassive star may undergo bar-mode instability and fission into two components which both collapse (cf Begelman and Rees 1978).

Binaries involving black holes contract slowly and eventually coalesce. The longest-lived phases, in which such systems stand the biggest chance of being observed, correspond to separations such that (r/r_s) lies in the range 3000 - 10^5 (corresponding to 10^{17} - 3×10^{18} cm for masses $\sim 10^8 M_\odot$): when the systems are tighter than this, gravitational radiation causes rapid coalescence; for separations exceeding this range, dynamical friction is efficient. For a given binary, the orbital period varies as $r^{3/2}$ and the precession period as $r^{5/2}$. "Wide" binaries with precession periods $\sim 10^8$ yrs may be responsible for the inversion-symmetric features in large-scale jets and double sources; closer binaries, with orbital periods $\sim$30yrs and precession periods $\sim 10^4$ yrs, may produce bending and misalignment in VLBI jets through the kinematic consequences of precession. This scenario has been investigated by Begelman *et al*. (1980).

3.4 Source Statistics

The naive (but very attractive) twin-jet model for superluminal sources (Blandford and Konigl 1979, Scheuer and Readhead 1979) attributes the range of L_{rad}/L_{opt} in quasars to orientation effects, on the hypothesis that the radio emission from the compact component is relativistically beamed. This model, in principle, offers specific productions about the bivarate radio-optical luminosity function. The luminosity function for the beamed radio continuum (and maybe also for the optical continuum if this is beamed as well) should be broader than the luminosity spread in the emission lines or any other isotropic component. But the failure of the most straightforward predictions need not be fatal to the general scheme - it could mean only that the model is unrealistically oversimplified. Complications such as a spread in Lorentz factor between sources (and even a range of Lorentz factors and ejection angles within each source) should probably be allowed for; when data are available on the distribution of L_{rad}/L_{opt}, the equivalent width of lines, etc. for larger samples of optically-selected quasars (cf Smith and Wright 1980, Condon et al. 1980, Strittmatter et al. 1980) it will be worthwhile exploring these refinements.

Even the present restricted data, however, confront the model with an embarassment: 3C 273, the brightest optical quasar in the sky (in terms of its line and continuum flux), is a superluminal radio variable. This requires an object which is already exceptional by other criteria to have a preferred orientation that has only a $\sim$ 1% probability ($\sim \gamma_b^{-2}$, where the superluminal behaviour requires $\gamma_b \gtrsim 5$). This betokens the desirability of modifying the simple scheme. There are a number of possibilities, of which the following is one:

The relativistic plasma may emerge over a spread of angles, rather than solely along the beam axis. Retaining the assumption of axisymmetry, we can suppose that the material is ejected over a range of directions making angles ϕ with the symmetry axis, in such a way that $\gamma_b = \gamma_b(\phi)$ and $\mathcal{S} = \mathcal{S}(\phi)$. For illustrative purposes, suppose γ_b is the same for all ϕ and that only the "specific discharge" depends on ϕ. Then the superluminal velocities of order γ_b c will be manifested to an observer whose line of sight makes an angle ϕ_o with the axis of symmetry by portions of the material within the hollow cone defined by the angles $(\phi + O(\gamma_b{}^{-1})) - (\phi_o - O(\gamma_b{}^{-1}))$. The dominant superluminal effects will be on one side of the centre, and will appear - in projection - aligned with the axis on the approaching side, if $\mathcal{S}(\phi_o - O(\gamma_b{}^{-1}))$ dominates $\mathcal{S}(\phi_o + O(\gamma_b{}^{-1}))$ by a sufficient factor. For instance one possible form for $\mathcal{S}(\phi)$ guarenteeing this would be $\mathcal{S}(\phi) \propto \exp(-K\phi)$, with $K \gtrsim \gamma_b{}^{-1}$.

To show how this eases the problem of explaining why 3C 273 is a superluminal source, suppose that $\gamma_b \simeq 5$ but that our line of sight makes an angle $\sim 45^o$ with the symmetry axis. We would see superluminal effects, although the radio emission would then be only e^{-3} as strong as if we had the optimal alignment. However, the apparent value of L_{rad}/L_{opt} is higher in 3C 279, which is 3 magnitudes fainter than 3C 273 in the optical but has a similar radio flux. Thus, the relatively weak superluminal components of 3C 273 can be explained as the "sidelobes" of the main directed discharge.

4. COLLIMATION OF JETS

Almost all collimation mechanisms involve the preferential escape (or acceleration) of material along "directions of least resistance"; these directions are likely to be related to a rotation axis within the galactic nucleus. One class of possibilities involves the 'twin exhaust' nozzle (Blandford and Rees 1974, 1978b; Rees 1976) in which buoyant material surrounded by a rotating gravitationally bound cloud escapes via two beams. The confinement is provided by a gravitationally bound cloud in the central potential well; within this cloud lies a source of gas which is very buoyant (in the sense that its value of (P/ρ) much exceeds the gravitational binding energy) and may be relativistic. If the gravitationally bound cloud is flattened, owing to rotation and/or the shape of the potential well, the buoyant fluid emerges along the minor axis. If a steady flow pattern establishes itself, its form is calculable provided that the $p(\rho)$ relation for the buoyant fluid is known. A nozzle forms where the external pressure drops to about half the stagnation pressure; further out, the flow is supersonic, and the channel slowly broadens as the external pressure drops off. This general mechanism does not require any pressure anisotropy in the fluids concerned.

The width of the channel adjusts itself so that there is pressure balance across the walls. The channel cross-section is proportional to the energy flux carried by the jets, and varies inversely with the pressure in the external cloud.

4.1 The Properties of the Gravitationally Bound Confining Cloud

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. Blandford and Rees (1974) envisaged that the cloud was confined within a flat-bottomed potential well due to the stars in the inner region of the galaxy, and supported by gas pressure. This required temperatures in the Kev range, implying that the cloud would itself be a source of X-rays.

If the confining cloud were much more compact, and in a deeper potential well, a higher value of P/ρ would be needed to support it. For clouds around massive black holes, where P/ρ may exceed m_ec^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 (or thick disc or "donut") in a relativistically deep potential well:

(i) 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 too rapidly.) Or (ii) the cloud is 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 at temperature T_{rad} and the gas kinetic temperature will also be T_{rad}. If radiation pressure provides the primary support, the leakage of energy must correspond to the "Eddington luminosity" for the central mass.

4.2 General-Relativistic Features of the Flow

Most features of galactic nuclei are probably insensitive to the details of the metric in the relativistic part of the potential well (and therefore are almost independent of which theory of gravity is the right one). But there are two features of the flow pattern around collapsed objects which are distinctively relativistic and play an important role in constraining the behaviour of inflowing gas.

Near a spinning black hole the Lense-Thirring dragging of inertial frames can enforce axisymmetry with respect to the hole's rotation axis, even if the inflowing material possesses angular momentum in an oblique direction. An orbit of radius r and period t_{Kep} precesses on a timescale $t_{prec} = t_{Kep}(J/J_{max})^{-1}(r/r_s)^{3/2}$, J being the hole's angular momentum and J_{max} the maximum angular momentum of a Kerr hole. If the material drifts in only slowly (ie if the viscosity is low enough that $t_{infall}(r) >> t_{Kep}(r)$) then the precession builds up over many orbits. As Bardeen and Petterson (1974) pointed out, there is then a critical radius r_{BP}, at which $t_{prec} = t_{infall}$. For $r \lesssim r_{BP}$ the gas flow is axisymmetric with respect to the hole irrespective of the original angular momentum. Thus, if the beams are collimated at a radius $\lesssim r_{BP}$, their orientation is, in effect, controlled by the 'gyroscopic' effect of the hole: they are then impervious to jitter resulting from small-scale fluctuations in the flow pattern of the surrounding gas, and can swing or precess only in response to changes in the hole's spin axis.

A second distinctive feature of black holes is that there is a maximum amount of angular momentum which can be swallowed by the hole. This is essentially the specific angular momentum of the circular orbit of zero binding energy (which is located at r = 4M = $2r_s$ for a Schwarzschild hole). For an axisymmetric flow pattern, we can consequently delineate a 'region of non-stationarity' around the rotation axis. This region, roughly paraboloidal in shape, is bounded by the circular orbits of zero binding energy whose angular momentum equals the critical value. No stationary axisymmetric bound flow can extend into this region. All the material within it must either have positive energy (in which case it will escape) or else has so little specific angular momentum that it falls freely into the hole. Not surprisingly, the 'walls' bounding this "region of non-stationarity" figure in several specific models accounting for the production of collimated jets.

4.3 Thick Discs or "Donuts"

If material with angular momentum is able to cool, it forms a thin centrifugally-supported disc whose structure is relatively simple. But discs becomes more complicated when the thickness h(r) becomes comparable with the radius r. Pressure gradients in the radial direction are then comparable to those in the perpendicular direction; consequently the angular velocity can no longer be assumed exactly Keplerian. The structure of such discs involves more degrees of freedom than for thin discs; the angular momentum is a free parameter, subject to certain constraints. The most thorough investigations of thick discs have been carried out by the Warsaw group (Paczynski, Jaroszynski, Abramowicz, Sikora, Koskowski) is a series of papers, following earlier work by Fishbone and Moncrief (1976) and Lynden-Bell (1978). Attention has been focussed on optically thick discs supported primarily by radiation pressure. The authors of this work have been concerned with application to quasars (and have supposed that the primary photo-ionizing continuum in quasars may be the ultraviolet thermal emission from the outer part of the disc, radiating at the Eddington luminosity). These specific models do however help us to develop a feel for thick discs and rotating clouds in general, and their role in the production of beams.

The angular momentum distribution is subject to some constraints. For instance, stability may require that the specific angular momentum increases outwards; if viscosity is to cause material to drift inward, then the angular velocity must decrease outwards. If the inner edge of the disc in the equatorial plane lies at r_i, then r_i must lie between r_o, the radius corresponding to a circular orbit of zero bounding energy, and r_{ms}, the radius of the minimum stable Keplerian orbit.

The following comments can be made about thick discs in general, whether their pressure support comes from trapped radiation, or from ions with high kinetic temperature.

(i) The shape of the disc is determined by the surface distribution of angular momentum. Once this is specified, the binding energy over the surface is determined. In the limiting case where the angular momentum is constant, and the binding energy at r_i tends to zero (i.e. r_i is close to r_o) the 'donut' would be bounded by the paraboloidal "region of non-stationarity".

(ii) The shape of the isobars within the 'donut' depends on the internal equations of state, and on the internal distribution of angular momentum. (The arbitrariness of the latter can be reduced by imposing the "von Zeipel condition" for stability of a barytropic rotating fluid - the relativistic generalisation of the requirement that the angular velocity is constant on cylinders around the rotation axis. However, there is no obvious reason for requiring barytropicity, nor for excluding convective or circulatory motions). The pressure

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maximum must always occur in the equatorial plane at a radius outside r_{ms}, where the rotation velocity is Keplerian. Outside this radius the rotation rate is slower than Keplerian because the pressure gradient is directed outwards. In the limit of very thick and extensive 'donuts', where the angular momentum is low, the pressure-density relation can be almost isotropic except in a narrow "funnel" near the rotation axis.

The 'donuts' supported by radiation pressure would have approximately $\rho \propto r^{-3}$ away from the axis. They can have a large overall extent (i.e. a "photospheric radius" $r_{phot} >> r_i$) only if they are very optically thick in the inner parts. This implies that the viscosity, parameterised by the α-parameter introduced by Shakura and Sunyaev (1973), must be very low ($\alpha < (r_{phot}/r_s)^{-2}$).

These 'donut' configurations obviously have the right shape to aid the collimation of energy released near a central black hole.

4.4 Narrowing of the Beam Angle

The "twin-exhaust" configuration (or its generalisation to the 'donut' geometry) is naturally able, by purely hydrodynamical processes, to produce an initial bifurcation of the outflow into two beams along the rotation axis. Another rather different possibility utilises the anisotropic stress from an ordered magnetic field. If such a field is initially aligned along the rotation axis of a disc, and is then sheared (and rendered almost axisymmetric) by strong differential rotation, it can exert a strong torque and generate outflow along the field lines which will be (to some extent) directed along the rotation axis (Blandford 1976).

But even when the outflow has become sufficiently collimated to be supersonic (i.e. a directed velocity > $c/\sqrt{3}$ if the beam consists of ultrarelativistic matter) its collimation can be improved if it propagates outward under conditions of transverse pressure confinement. A beam emerging from the nucleus of a galaxy may pass through a region of steadily decreasing ambient pressure for up to several tens of kiloparsecs. Even if the beam is confined, and its flow obeys Bernoulli's equation, this decrease in pressure will result in an increase in cross-section; but the degree of collimation can still increase, if the diameter of the channel d increases less rapidly than the distance from the nucleus, r. This is well outside the region where supersonic flow begins, so the flux of bulk kinetic energy does not change significantly in this region if there is no entrainment. For an equation of state $p \propto \rho^{\Gamma}$ (not necessarily adiabatic) and a pressure run $p \propto r^{-n}$, the opening angle of the jet $\theta \sim d/r$ varies as

$$\theta \propto r^{(n - 2\Gamma)/2\Gamma} \qquad (6)$$

for a non-relativistic equation of state in the jet, and $\theta \propto r^{(n - 4)/4}$ for $c_s \simeq c/\sqrt{3}$. The Mach number varies as $r^{(\Gamma - 1)n/2\Gamma}$ and $r^{n/4}$,

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respectively. Collimation increases with decreasing n and increasing Γ, i.e., with a harder equation of state. The jet composed of ultra-relativistic fluid is easiest to collimate, since the formula for θ corresponds to setting $\Gamma = 2$ in equation (6), although the equation of state in the comoving frame has $p \propto \rho^{4/3}$. If resistance to sideways compression is dominated by conserved angular momentum about the jet axis or a longitudinal magnetic field, then the effective Γ also equals 2.

The confining cloud is likely to extend to large r, but with density decreasing outwards. For a cloud with an equation of state $p \propto \rho^{\Gamma_c}$ surrounding a point mass, $n = \Gamma_c/(\Gamma_c - 1)$. Thus, a jet of nonrelativistic gas with $4/3 < \Gamma < 5/3$ will be decollimated unless Γ_c exceeds 10/7. A radiation-dominated isentropic atmosphere ($\Gamma_c = 4/3$) cannot enhance collimation, although the jet may have originated in a thick disk of radiation-dominated gas. Where convergence does occur within a hydrostatic atmosphere it is in general rather slow.

Semi-empirical estimates of the mean pressure run over larger distances offer greater hope for effective pressure collimation. The pressure in the vicinity of a 10^8 $M_\odot$ black hole ($\sim 10^{14}$ cm) is unlikely to exceed 10^8 dyne cm^{-2}, while the pressure at $\sim$ 1 pc is typically of order 10^{-2} dyne cm^{-2} for VLBI jets such as NGC 6251 as well as for the broad emission line regions of quasars. This gives a mean value for n of about 2, resulting in considerably better collimation than one obtains with the $n = 5/2$ hydrostatic atmosphere which corresponds to $\Gamma_c = 5/3$. In the five decades of radius between the black hole and where we see VLBI jets, more than 20-fold collimation can occur for $\Gamma > 4/3$, with as much as 300-fold collimation possible for a jet with an ultrarelativistic equation of state. This is more than adequate to explain the apparent opening angles, $\theta \sim 3^o - 10^o$, which have been observed in VLBI jets.

If cooling occurs in the beam material, this aids collimation by reducing the internal pressure; conversely, viscous effects cause the beam to broaden. A further interesting possibility is that the magnetic field in the beam may establish a transverse self-focussing pattern.

The run of pressure with radius is of course unlikely to follow a smooth power law over the many decades of r which are relevant to the radio observations. If p becomes very small, or falls off suddenly with increasing radius, the beam may become a "free jet" expanding sideways (in its own frame) at its internal sound speed. Free jets must have Mach numbers exceeding θ^{-1}; they are of course not so vulnerable to Kelvin-Helmholtz instabilities.

It is possible that beams produced deep in a galactic nucleus can be destroyed by instabilities, and then re-collimated on a larger scale. In this case the orientation of the larger-scale beams would reflect the overall shape of the galaxy, rather than its nucleus;

characteristic differences between the radio morphology of spirals and ellipticals could be a consequence of the different gaseous environments in these systems (Shu and Sparke 1980).

4.4 Stability, etc.

Even if equilibrium flow patterns exist that can give rise to beams, 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 model calculations of stability, when they are applied to the flow of magnetised (possibly relativistic) plasma flowing through a medium of uncertain properties. Kelvin-Helmholtz instabilities can occur anywhere along the beam's path but even more serious is the possibility that Kelvin-Helmholtz and Rayleigh-Taylor instabilities (both of which could in principle occur in the nozzle region) can prevent the collimated flow from ever being set up.

Several authors (e.g. Wiita 1978, 1980, Smarr et al. 1980) have attempted 2-D numerical calculations of how the 'twin exhaust' flow pattern might be established. A gravitationally bound cloud is taken to be already established in a flat-bottomed potential well; the central source of 'hot' plasma is then switched on; it inflates a bubble, which finally breaks out along the minor axis; in some cases, a quasi-steady flow pattern may then be set up. the most recent calculations along these lines are those of Smarr et al. (1980). They 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). While these calculations are the best we yet have, they are 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 protrusions around the flow boundary. It is not obvious whether this underestiamtes or overestimates the instability - these axisymmetric perturbations are harder to excite than a localised perturbation; on the other hand, once they are formed, their effect on the flow is more drastic.

If the collimation occurs close to a massive black hole - especially if it occurs in the domain where Lense-Thirring precession can enforce axisymmetry - the confining cloud lies in a potential which is approximately of the form r^{-1}, rather than being flat-bottomed. As Blandford and Rees (1974) already recognised, this may make it harder to establish a stable twin exhaust geometry. The pressure in the cloud would fall off as $\sim r^{-4}$ (if supported by radiation pressure) or as $\sim r^{-5/2}$ (if supported by ion pressure); in either case, this fall-off is so steep that a homologous perturbation of an equilibrium flow may lead to instability. If, however, the confining cloud possesses some angular momentum, so that its pressure distribution has the form expected in the 'donut' configuration, the prospects for stability are much improved.

This is because the pressure can in principle rise by several orders of magnitude as one moves out from the 'zone of non-stationarity'. Even a drastic change in the power of the central source need therefore cause only a small enlargement of the channel. In computing such flow patterns, rotational effects in the jet material itself should also be taken into account.

If the collimation is established on scales $\lesssim 10^2\ r_s$, it ceases to be realistic to regard the confining cloud and the expelled jet material as separate entities: each is part of a rotational flow pattern in the gravitational potential well of a relativistic central body. Conditions in the cloud can change on the same timescale as the jet flow itself; the flow may involve continuous gradations in (P/ρ) rather than two distinct components.

5. PRODUCTION OF BEAMS WITH $\gamma_b \gtrsim 5$

5.1 Electron-positron pairs

The VLBI data imply that, in the cases of the superluminal sources at least, γ_b is in the range 5 - 10. (As explained in section 3, 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. (If the jet production involves a transition from subsonic flow through a nozzle, then the material must start off with a thermal energy per particle of this order). This is a general difficulty with purely gas-dynamical processes; it suggests that a different process must be invoked. Two possibilities are:

(i) Hydromagnetic mechanisms which channel most of the energy of infalling matter into a small fraction of the particles. This sort of process is envisaged to occur near the light cylinder of pulsars. In extreme cases (Lovelace 1976, Blandford 1976) beams with $\gamma_b \gtrsim 10^{10}$ could be generated.

(ii) The beams may consist of $e^+ - e^-$ plasma rather than containing ions; $\gamma_b \simeq 10$ can then be attained with only $\sim$ 10 Mev rather than $\sim$ 10 Gev per electron.

These two possibilities are not disjoint: some pulsar models involve the production of cascades of $e^+ - e^-$ pairs, and similar processes can happen around black holes (Blandford and Znajek 1977).

There are, however, more mundane ways of generating $e^+ - e^-$ pairs: indeed their creation is unavoidable in a compact region containing high energy particles, emitting X-rays and gamma-rays. If the X-ray luminosity (characteristic photon energy ε) is L_X, then the optical depth of the core region to a gamma-ray of energy $> 2(m_e\ c^2)^2/\varepsilon$ is

$\sim 10^2 \; (L_X/L_E) \; (\varepsilon/m_e c^2)^{-1}$

Unless the X-ray luminosity is very low, any radiation process in the core that generates gamma-rays automatically yields $e^+ - e^-$ pairs.

An obvious constraint on electron-positron beams is that their constituent particles must not annihilate. Defining γ_{random} as the mean Lorentz factor of the particles, measured in a comoving frame, the energy flux is

$$\left(\frac{\pi \; d^2}{4}\right) m_e \; c^2 \; n_e \; c \; \gamma_b^{\;2} \; \gamma_{random}$$

The annihilation timescale, measured again in the moving frame, is $\sim (n_e c \; \sigma_T / \; \gamma_{random}^2)^{-1}$. If the jet originates at a very small radius, this implies that it cannot carry a large energy discharge unless γ_b is large; otherwise it will annihilate. (As a parenthetical remark, note however that a gamma-ray beam resulting from such annihilation is an efficient loss-free mechanism for transporting energy out of a strongly magnetised core region. The gamma-rays could eventually reconvert into pairs after propagating for a few parsecs by interacting with X-rays in the galaxy, thus providing, in effect, an "in situ" acceleration mechanism for $e^+ - e^-$.)

5.2 Radiation Pressure

Radiation pressure on free electrons balances gravity if the luminosity L equals the well-known "Eddington luminosity" $L_E = 4\pi \; G m_p M c/\sigma_T$ (This expression for L_E assumes that the Thomson cross-section is applicable, and that the material is primarily hydrogen; modifications to allow for other possibilities are straightforward). If the effective luminosity exceeds L_E (or if, even for lower L, the appropriate cross section σ exceeds σ_T) radiation pressure accelerates material outwards. In the non-relativistic approximation, the terminal speed of a particle released from radius r_1 is of order $[(L - L_E)/L_E]^{\frac{1}{2}} \; (GM/r_1)^{\frac{1}{2}}$. There is therefore a chance of attaining relativistic velocities if the acceleration starts from a compact object, with r_1 only a few times larger than r_s. Even if L exceeds L_E by orders of magnitude, there is no great likelihood of achieving <u>very</u> high Lorentz factors. This is because, when the velocities get relativistic, the terminal γ_b rises only rather slowly with L/L_E. If the source of radiation is extended, the acceleration saturates at a value of γ_b such that aberration shifts some of the radiation (in the electron's frame) into the forward direction. (These effects are still important even in an electron-positron plasma, where the inertia per unit cross-section is lower by $\sim$ 1840). Relevant calculations are presented by Jaroszynski <u>et al</u>. (1980). A specially interesting possibility arises in the cases of thick 'donuts' supported by radiation pressure. The radiation emerges anisotropically, being especially intense along directions close to the rotation axis. This is because centrifugal effects greatly enhance the effective gravity on the walls of the 'funnel' around this axis. Accurate estimates of this effect, even in idealised models, are complicated because of reflection effects in the 'funnel' (cf Abramowicz and Piran 1980). However, Sikora (1980) finds that, for a 'donut' whose photosphere extends out to 500 r_s, the specific intensity in directions within 15^o of the axis is $\gtrsim 70\ L_E$. While this implies that any material expelled by radiation pressure would preferentially lie in jets along the rotation axis, the gain in terminal speed resulting from the collimation is meagre: the high ambient density of radiation within the funnel provides a compton drag which prevents the attainment of relativistic speeds until the material reaches the outer radius of the donut; thick donuts permit large values of (L/L_E) along the axis, but this is compensated by the fact that the effective r_1 is then large.

6. SOME FURTHER QUESTIONS REGARDING THE PHYSICS OF BEAMS

The obvious key issues concern the flow pattern in the region where the beams are formed, the beam speed, the nature of the collimation mechanism and the stability. Collimation may occur in the relativistic domain near a black hole, but it is unclear whether it is basically a fluid-dynamical process or whether a crucial role may be played by electromagnetic effects, anisotropic radiation pressure, etc. The jet could conceivably comprise electron-positron pairs rather than ordinary matter; it may contain a magnetic field, or even carry a current (Lovelace 1976, Benford 1979). The radio emission - even the milli-arc-second structures seen by VLBI techniques - involvesscales vastly larger than the primary energy source. If some of the extreme cases of optical variability involve directed relativistic outflow (Blandford and Rees 1978a, Angel and Stockman 1980) they may provide clues to jet behaviour on rather smaller scales.

Even though the jets may be moving at a high (or even relativistic) speed the material in them could cool down to a low temperature, yielding a high Mach number and the possibility of unconfined "free jets". A dense jet emanating from near $r \simeq r_s$ with an energy flux of order L_E could certainly cool to a non-relativistic value of T_e. But such a jet would only be directly observable if:

(i) internal magnetic field energy were dissipated and partially converted into relativistic electrons;

(ii) friction and entrainment at the jet boundaries (or interaction with "obstacles" in the jet's path) dissipated some of its bulk kinetic energy; or

(iii) the ejection velocity were variable, and thus led to the development of internal shocks, which accelerated relativistic electrons. (cf Rees 1978c).

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The fact that the jet in, for instance, NGC 6251 is detectable at all, means that some re-randomisation of kinetic energy and reacceleration of particles must be occurring along its length to counteract radiation and adiabatic losses. Even the thermal component of the beam material may have a large enough emission measure to be detected (cf the X-ray jet in Cen A, though this could alternatively involve non-thermal emission).

The radio observations of curvature in jets indicate that the physics can be further complicated by such effects as transverse motion of an external medium, buoyance, misalignment of the galaxy with the spin axis of its central black hole, and possible precession of the hole itself.

The range and complexity of realistic beams would much surpass the simple idealised models discussed above. For instance, a beam whose volume is filled predominantly by relativistic plasma may contain cool material embedded in it, owing to

(i) injection of such material in the nucleus

(ii) entrainment from the surrounding medium

(iii) obstacles (e.g. supernova remnants, planetary nebulae) in the path of the jet.

or (iv) cooling of ejected material (via bremsstrahlung etc.), leading to thermal instability, if $t_{cool} \lesssim t_{outflow}$ just outside the nozzle.

For any of these reasons, one may expect cool, relatively dense clouds embedded in the beam plasma, in pressure balance with it, and coasting out with speed $\sim V$, (a scaled-up version of the gas in the SS 433 jets that produces the emission lines). This may be relevant to the large double sources such as DA 240 where there seem to be several hot spots. Smith and Norman (1980) attribute these to separate blobs ploughing supersonically through the intergalactic medium and being decelerated at different rates.

An extreme possibility is that the blobs condensing out may become self-gravitating: having been accelerated to a high (even relativistic) speed, some beam plasma could cool and condense into stars or supermassive objects. This requires rather extreme conditions; it illustrates, however, the wealth of possibilities that can be incorporated within the beam model. If the evidence for anomalous redshifts, "quasars" shot out of galaxies, etc. were ever to become compelling, then these possibilities should be explored before feeling driven to invoke new physics.

7. ACCRETION FLOWS, COOLING, AND SCALING

7.1 The Cooling Timescale Versus the Collapse Timescale

If material falls radially into a black hole, then the efficiency (i.e. the fraction of the rest mass radiated before being swallowed) is small (cf Shapiro 1973, Rees 1978b). This is because, for radial infall, $t_{cool} \propto \dot{M}^{-1}$ whereas t_{infall} is independent of $\dot{M}$. It is perhaps less evident that this low efficiency cannot necessarily be 'cured' by introducing angular momentum. Interestingly, however, this proves to be the case.

Suppose that an accretion disc bulges up, owing to internal viscous dissipation, until its thickness h is of order the radius r. The inward drift timescale $\sim t_{Kep}(h/r)^{-2}\ \alpha^{-1}$ is then of order $\alpha^{-1}t_{Kep}$, α being the usual viscosity parameter. If the primary agent for viscosity is a tangled-up magnetic field, then the effective α will depend on the time-averaged field geometry and the rate of reconnection (which determine the ratio of Alfven and Keplerian speed). There is, however, no reason why the effective α arising from magnetic viscosity should depend at all sensitively on $\dot{M}$.

This means that as $\dot{M} \to 0$, t_{inflow} becomes a fixed multiple of t_{Kep}; but the cooling time becomes arbitrarily long in this limit. In other words, angular momentum can be redistributed much faster than the binding energy is radiated away. When $\dot{M}$ is sufficiently low, what must therefore happen is that the inner parts of the disc resemble a 'donut' extending in almost to the location, r_o, of the orbit of zero binding energy. Material that loses enough angular momentum to reach such an orbit can spill into the hole without having radiated significant binding energy.

This flow pattern may well be the norm in galactic nuclei containing massive black holes ('dead quasars') but where the fuelling rate has now fallen very low, to a value corresponding to $\dot{M}/\dot{M}_{crit} << 1$. The only perceptible radiation emitted from such objects would be due to a non-thermal tail of electrons (accelerated behind shocks, or by processes related to the magnetic reconnection and viscosity). The pressure distribution of the hot thermal plasma (in which $T_i > T_e$) - apart from a 'funnel' along the rotation axis - would be approximately of the form $p \propto r^{-5/2}$ at large distances from the hole. This cloud may be responsible for the collimation of jets and beams from such systems. The high-entropy plasma escaping in the beam could be produced by exotic processes near the hole (maybe involving Blandford-Znajek (1977) electromagnetic effects).

An example of an active galactic nucleus with $\dot{M} << \dot{M}_{crit}$ is M 87. If it indeed contains a black hole of $5.\ 10^9\ M_\odot$, as has been claimed (Young et al. 1978), then the level of activity in the nucleus yields only 10^{-4} of the critical luminosity. This nucleus certainly cannot contain a radiation-supported 'donut' emitting at the Eddington

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luminosity; on the other hand, provided magnetic (or any other) viscosity yields $\alpha \gtrsim 10^{-2}$, the cooling timescale for thermal plasma accreted onto it could still be longer than the inward drift timescale, allowing the possibility of a cloud supported by ion pressure. The compact radio source in the nucleus of M 87 displays no superluminal effects; nor is it apparently aligned along the jet. Non-thermal emission from a quasi-spherical cloud could account for this emission. Over a range of radii; one would expect $B \propto r^{-5/4}$; the observed radiation would be the sum of contributions from different radii, the self-absorption turn-over occurring at higher frequencies for smaller r.

7.2 Scaling Laws

The flow pattern when accretion occurs is determined by the values of the parameters L/L_E (which determines the relative importance of radiation pressure and gravity) and the ratio t_{cool}/t_{inflow}. If $\dot{M}$ is scaled in proportion to M, there is no reason why accreting objects of very different mass should not involve similar flow patterns: t_{cool}/t_{inflow}, α, the radiative efficiency, and L/L_E would then be independent of M.

So the apparent analogy between stellar-scale phenomena (SS 433, Sco X1 etc.) and active galactic nuclei may indeed reflect a close physical similarity. The relevant parameter is $\dot{M}/\dot{M}_{crit}$ ($\propto L/L_E$ for a given efficiency):

	$L/L_E \approx 1$	$L/L_E << 1$
$M = 10^9\ M_\odot$	Quasars	M 87
$M = (1 - 10)\ M_\odot$	SS 433	"radio stars" γ-ray sources

Just as M 87 and similar low-luminosity active nuclei may display the most purely non-thermal emission (because the cooling time for non-relativistic gas is too long); so these objects may have small-scale counterparts in our Galaxy, detectable only in the radio (and maybe also the gamma-ray) band.

8. CONCLUDING REMARKS

This is a cosmic ray conference. I should therefore attempt, before concluding, to relate galactic nuclei and radio sources to the theme of cosmic rays.

(i) The central cores of galactic nuclei, where irregular bulk velocities comparable with c are inevitable, are the most efficient sites (apart possibly from pulsar magnetospheres) for the production of fast particles. All the particles may be at least mildly relativistic; a variety of electromagnetic processes can generate some particles with high γ.

(ii) The central cores, and the beams emerging from them, could conceivably be composed of electron-positron plasma.

(iii) There must be regions within extended radio sources - in the "hot spots" now resolvable by the VLA - where the bulk kinetic energy of beam plasma is being randomised, and particle acceleration is occurring by processes qualitatively similar to those encountered in more local contexts such as the solar wind.

(iv) The cumulative debris from all extended radio sources must have built up a relativistic particle flux pervading the entire intergalactic medium. Electrons with $\gamma > 200$ lose their energy within the Hubble time via the inverse Compton effect, but the ions will accumulate. Even if (as now seems unlikely) most of the X-ray background came from these intergalactic electrons, the associated ions would contribute a universal flux of only a few times 10^{-3} ev/cc(Rees and Setti 1968) even if we assume the traditional 100:1 factor favouring ion acceleration over electrons. Any intergalactic magnetic field is likely also to be primarily the relic of radio source activity.

(v) Cosmic rays of the very highest energy ($\gtrsim 10^{19}$ ev), commonly thought to be of extragalactic origin, could have been accelerated in the lobes of extended nearby double sources: the product of length scale and field strength in these lobes is large enough that statistical acceleration mechanisms could operate at these energies (Cavallo 1978). The central cores of active galaxies are less promising sites because of the high photon density associated with them.

To sum up: it seems that the phenomena of active galactic nuclei are beginning to fit into a pattern. It is at least clear what physical processes are the main ingredients of a model and should be explored further. In particular, the formation of beams seems a generic property of the flow pattern around collapsed objects, where there is a relativistically deep potential well. These beams are relevant to extended radio sources, "superluminal" variations in compact sources, and the injection of high-energy plasma into the intergalactic medium.

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REFERENCES

Abell, G.O. and Margon, B.: 1979, Nature, 279, p. 701.
Abramowicz, M. and Piran, T.: 1980, preprint.
Angel, R. and Stockman, P.: 1980, Ann. Rev. Astr. Astrophys. (in press).
Bardeen, J. and Petterson, J.A.: 1974, Astrophys. J. (Lett), 195, L.65.
Begelman, M.C., Blandford, R.D. and Rees, M.J.: 1980, Nature (in press).

Begelman, M.C. and Rees, M.J.: 1978, Mon. Not. R. astr. Soc., 185, p.847.
Begelman, M.C., Rees, M.J. and Blandford, R.D.: 1979, Nature, 279, p.770.
Bekifi, G., Feld, B.T., Parmentola, J. and Tsipis, K.: 1980, Nature, 284, p.219.
Benford, G.: 1979, Mon. Not. R. astr. Soc., 183, p.29.
Blandford, R.D.: 1976, Mon. Not. R. astr. Soc., 176, p.465.
Blandford, R.D. and Konigl, A.: 1979, Astrophys. J., 232, p.34.
Blandford, R.D., McKée, C.F. and Rees, M.J.: 1977, Nature, 267, p.211.
Blandford, R.D. and Rees, M.J.: 1974, Mon. Not. R. astr. Soc., 169, p.395.
Blandford, R.D. and Rees, M.J.: 1978a, in "B.L. Lac Objects" ed. A. Wolfe (Pittsburg).
Blandford, R.D. and Rees, M.J.: 1978b, Physica Scripta, 17, p.265.
Blandford, R.D. and Znajek, R.L.: 1977, Mon. Not. R. astr. Soc., 179, p.433.
Burbidge, E.M., Smith, H.E. and Burbidge, G.R.: 1975, Astrophys. J. (Lett), 199, L.137.
Butcher, H., Van Breugel, W. and Miley, G.: 1980, Astrophys. J. (in press).
Cavaliere, A. and Morrison, P.: 1980, Astrophys. J. (Lett), 238, L.63.
Cavallo, G.: 1978, Astron. Astrophys., 65, p.415.
Condon, J.J. et al.: 1980, Astrophys. J. (in press).
Fabian, A.C. and Rees, M.J.: 1979, in "X-ray Astronomy" ed. W.A. Baity and L.E. Peterson (Pergamon).
Fishbone, L.G. and Moncrief, V.: 1976, Astrophys. J., 207, p.962.
Jaroszynski, M., Abramowicz, M.A. and Paczynski, B.: 1980, Astron. Acta, 30, p.1.
Jones, T.W. and Owen, F.N.: 1979, Astrophys. J., 234, p.818.
Longair, M.S., Ryle, M. and Scheuer, P.A.G.: 1973, Mon. Not. R. astr. Soc., 164, p. 243.
Lovelace, R.V.E.: 1976, Nature, 262, p.649.
Lovelace, R.V.E., MacAuslan, J. and Burns, M.: 1979, in Proceedings La Jolla Workshop on Particle Acceleration Mechanisms (A.I.P.)
Lynden-Bell, D.: 1978, Physica Scripta, 17, p.185.
Maraschi, L., Perola, G.C., Reina, C. and Treves, A.: 1979, Astrophys. J., 230, p.243.
Marscher, A.P. and Scott, J.S.: 1980, PASP, 92, p.127.
O'Dell, S.L.: 1979, in "Galactic Nuclei" ed. C. Hazard and S. Mitton (CUP)
Readhead, A.C.S.: 1979, in "Objects of Large Redshift", ed. G.O. Abell and P.J.E. Peebles (Reidel).
Readhead, A.C.S., Cohen, M.H., Pearson, T.J. and Wilkinson, P.N.: 1978, Nature, 276, p.768.
Rees, M.J.: 1976, Comm. Astrophys. & Sp. Phys., 6, p.112.
Rees, M.J.: 1978a, Nature, 275, p.516.
Rees, M.J.: 1978b, Physica Scripta, 17, p.193.
Rees, M.J.: 1978c, Mon. Not. R. astr. Soc., 184, 61P.
Rees, M.J.: 1980, in "X-ray Astronomy" ed. R. Giacconi and G. Setti (Reidel).
Rees, M.J. and Setti, G.: 1968, Nature, 217, p.362.
Scheuer, P.A.G. and Readhead, A.C.S.: 1979, Nature, 277, p.182.

Schreier, E. et al.: 1979, Astrophys. J. (Lett), 234, L.30.
Shakura, N.I. and Sunyaev, R.A.: 1973, Astron. Astrophys., 24, p.337.
Shapiro, S.L.: 1973, Astrophys. J., 180, p.531.
Shu, F. and Sparke, L.S.: 1980, Astrophys. J. (Lett) (in press).
Sikora, M.: 1980, Mon. Not. R. astr. Soc. (in press).
Smarr, L., Wilson, J. and Norman, R.: 1980, preprint.
Smith, M.D. and Norman, C.A.: 1980, Astron. Astrophys., 81, p.28.
Smith, M. and Wright, A.E.: 1980, Mon. Not. R. astr. Soc., 191, p.871.
Strittmatter, P.A., Hill, P., Pauliny-Toth, I.I.K., Steppe, H. and Witzel, A.: 1980, preprint.
Tubbs, A.: 1980, preprint.
Wiita, P.: 1978, Astrophys. J., 221, p.436.
Wiita, P.: 1980, preprint.
Wilson, D. and Rees, M.J.: 1978, Mon. Not. R. astr. Soc., 185, p.297.
Young, P.J. et al.: 1978, Astrophys. J., 221, p.721.

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