PHYSICS OF RELATIVISTIC JETS ON SUB-MILLIARCSECOND SCALES +

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1. INTRODUCTION

The observed superluminal components have (deprojected) lengths of $\sim 10^{20}$ cm, and imply relativistic bulk motions on these scales. There are, however, persuasive reasons for attributing the primary energy production to scales 10^{14} - 10^{15} cm. Moreover, the initial bifurcation and collimation must also be imposed on these small scales if the long-term stability of the jet axis in extended sources is due to the gyroscopic effect of a spinning black hole (Rees 1978). The issues I shall address in this talk are: how the jet gets from $\sim 10^{15}$cm to $\sim 10^{19}$ cm; and what VLBI data can tell us about the properties of galactic nuclei on scales below $\sim 10^{19}$ cm — scales where optical and X-ray studies provide some evidence, but where there is no short-term hope of achieving spatial resolution.

2. INTERNAL PHYSICS OF JETS ON SCALES 10^{15} - 10^{19} cm

The stuff ejected from $\sim 10^{15}$ cm may be electron-positron plasma or "ordinary" electron-ion plasma; reasons for seriously considering the former option are discussed elsewhere (e.g. Rees 1981, Guilbert, Fabian and Rees 1983). Energy can also be transported via Poynting flux - either as a large-scale field carried out with the particles (a directed MHD wind) or as low-frequency wave modes (cf. Rees 1971) — and this can, in principle, swamp the flux associated with the kinetic energy of the charged particles themselves. I shall show that there are severe constraints on e^+-e^- jets, particularly in quasars.

Suppose that a relativistic jet carries an energy flux $10^{45}L_{b45}$ erg s^{-1}, and has a cone angle $\theta(r)$. The region $r \lesssim 10^{15}$ cm may correspond to the "strong-field" domain around a black hole (the Schwarzchild radius r_s being related to mass by $r_s = 3 \times 10^{13}(M/10^8 M_\odot)$ cm), where the jet is energised by relativistic electrodynamic processes, and shaped by a disc or torus aligned with the hole's spin axis. I shall not discuss this region, but shall consider $r = 10^{15}r_{15}$ cm $\gtrsim 1$,

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where the jet can be assumed to be "coasting" - carrying a fixed total (internal plus bulk) energy - except insofar as internal radiative losses occur, or it interacts with the local environment (§ 3).

Annihilation constraints

Suppose that a fraction F_+ of the jet's luminosity is carried by e^+-e^- plasma, and that this (essentially charge-neutral) plasma moves outward with a bulk Lorentz factor γ_b; suppose further that the mean random motion has a Lorentz factor γ_r. The total particle flux along the jet is then proportional to $F_+ L_{b45} \gamma_b^{-1} \gamma_r^{-1}$ and the particle density in the comoving frame is proportional to $F_+ L_{b45} \gamma_b^{-2} \gamma_r^{-1} \theta^{-2}$. To check whether the particles will interact with each other (and cool and/or annihilate) we can calculate a "fiducial" cross-section σ_* such that a typical particle would undergo any process with at least this cross-section on the outflow timescale. We find

$$\sigma_*/\sigma_T = 0.02\ F_+^{-1}\ L_{b45}^{-1}\ \theta^2\ \gamma_b^3\ \gamma_r\ r_{15} \tag{1}$$

The mean number of times N_{Scat} that a photon in the jet would be scattered (with $\sigma \cong \sigma_T$) before escaping is

$$N_{Scat} = \sigma_T/\sigma_*\ \max\ [50\ F_+\ L_{b45}\ \gamma_b^{-1}\ \gamma_r^{-1}\ r_{15}^{-1}\ ; 1] \tag{2}$$

The two options in the square brackets correspond to the cases when the photon can or cannot diffuse through an angle $\sim \theta$, and thereby escape from the jet in the outflow timescale.

These numbers imply that, if $F_+ L_{b45} \cong 1$ (corresponding to a jet powerful enough to energise a strong double source or a superluminal component), then an e^+-e^- jet would be very optically thick at $r_{15} \cong 1$, unless γ_b and γ_r (in some combination) are sufficiently large. However, γ_r cannot itself be large, because the avoidance of runaway compton losses implies

$$N_{Scat}\ \gamma_r^2 \lesssim 1 \tag{3}$$

This holds provided that there is even a trivial supply of soft photons within the jet. If N_{Scat} is itself $\gtrsim 1$, this implies that the jet must be "internally cold", in the sense that the particles are sub-relativistic in the frame moving with Lorentz factor γ_b. But the annihilation rate (σ_{ann} V) for sub-relativistic pairs is then $\sim \sigma_T c$. This means that, on the outflow timescale, annihilation would reduce $F_+ L_{b45}$ until σ_T/σ_* (equation (1)) were ~ 1.

This argument tells us that the energy cannot emerge as e^+-e^- plasma unless the bulk Lorentz factor is high, the requirement being

$$\gamma_b \gtrsim 3.5\, F_+^{1/3}\, L_{b45}^{1/3}\, \theta^{-2/3}\, r_{15}^{-1/3} \tag{4}$$

If the jet material carried a magnetic field whose strength, in the comoving frame, was at least equivalent to equipartition with the random kinetic energy, then a simple argument shows that for $L_{b45} \cong 1$ and $r_{15} \cong 1$, synchrotron cooling would be rapid enough to reduce γ_r to a value ~ 1 on the outflow timescale. However, synchrotron cooling would be inhibited by reabsorption, and this would permit electrons and positrons with $\gamma_r > 10$ to persist if there were no other losses. But condition (3) implies that Compton processes would in any case ensure that γ_r was reduced to ~ 1 if N_{scat} were large. Synchrotron reabsorption therefore does not offer an "escape clause" to (4).

We can therefore conclude that the energy flowing along a jet at $r_{15} \cong 1$ must be in ordered motion or in Poynting flux: if the electrons were injected with high γ_r, (each therefore with total energy $\sim \gamma_r \gamma_b m_e c^2$) then the bulk of their energy would quickly be converted into a photon beam, with cone angle max $[\theta;\ \gamma_b^{-1}]$, only $\sim \gamma_b m_e c^2$ (i.e. $\sim \gamma_r^{-1}$ of the initial particle energy) surviving as directed kinetic energy.

Compton drag constraints

The same central engine which initiates the jets is also, presumably, the source of the primary continuum luminosity in the optical and X-ray bands; the particles in the jet will then exchange momentum with the photon flux via Compton scattering. The characteristic Compton timescale for a relativistic electron or positron in an isotropic photon field with energy density $L_{ph}/4\pi r^2 c$ can be expressed as

$$t_{comp}/t_{dyn} \cong 0.02\, L_{ph45}\, r_{15}\, \gamma^{-1}, \tag{5}$$

where $t_{dyn} = r/c$ is the dynamical timescale for relativistic outflow. This simple result tells us that, if $L_{ph45} \gtrsim 1$ (as it is in quasars) the interaction with the ambient radiation is very important; however, the nature of this interaction depends on the radiation's angular distribution. Some radiation escapes directly from the central source (which may have $r_{15} < 1$); part, however is scattered by gas at larger radii, or absorbed, and re-emitted isotropically mainly as emission lines. If the radiation was all directed outward from a small central source, or were itself collimated, the jet would tend to be accelerated; on the other hand, if the radiation were more nearly isotropic it would slow down a relativistic outflow on a timescale $\lesssim \gamma_b^{-1}\, t_{comp}$, where t_{comp} is given by (5). (I have written an inequality here to allow for the dependence on γ_r discussed by O'Dell (1981).)

A test particle released from rest into a flux of radiation would initially be accelerated at a rate $\sim c\, t_{comp}^{-1}$. However, when the particles are in a relativistic beam, what is relevant is the angular distribution and intensity of the radiation in the comoving frame.

There are two effects:

(i) The intensity in the beam frame of radiation directed along the beam is down by γ_b^{-2}; this fact, together with the time dilation factor, means that the terminal γ_b achievable by the pressure of radiation whose intensity falls off as r^{-2} scales only as $L_{ph}^{1/3}$ (see, for instance, Phinney (1982)).

(ii) When the radiation comes from a range of angles, then aberration will shift the apparent directions of some photons into the forward hemisphere, if γ_b is sufficiently high. For an angular distribution $I(\theta)$, axisymmetric around the beam direction, there will be a critical value of γ for which

$$\int_0^{\pi} I'(\theta') \cos\theta' \sin 2\theta' \, d\theta' = 0, \tag{6}$$

where dashes denote quantities transformed into a frame with Lorentz factor γ.

In a realistic quasar environment, radiation drag sets a significant limit on γ_b, even if the initial acceleration owes nothing to radiation pressure. This is because, when $\gamma_b \gg 1$, the acceleration due to radiation from behind can be outweighed by the drag due to a much smaller isotropic component. Let us define $L(r)$ as the luminosity which, in effect, emerges isotropically from shells with radii in the range $r - 2r$. Models for quasar emission lines imply $L(10^{18}\text{ cm}) \gtrsim 0.1 L_{ph}$ (where L_{ph} here denotes the total photon luminosity); we have no direct handle on $L(r)$ at smaller radii, but models of the intercloud medium suggest that its Thomson depth could be $\gtrsim 0.1$ (cf. § 4 below). This radiation provides a drag which limits γ_b to

$$(\gamma_b(r) - 1) < 0.02\, F_+^{-1}\, L_{ph45}^{-1}(r_{15})\, r_{15}. \tag{7}$$

We cannot quantify this further until models of the galactic nucleus allow $L(r)$ to be estimated for the whole range 10^{15} cm - 10^{19} cm. However, it is clear that (7) sets a significant upper limit on γ_b, especially for a pure e^+-e^- beam (for which $F_+ \cong 1$). This result, in conjunction with the earlier argument (relation (4)) that γ_b must be large if an e^+-e^- beam is to carry a high energy flux without annihilating, sets severe constraints on this type of beam. (The Compton drag on an electron-ion beam, given by (7) with $F_+ = 2(m_e/m_p) \cong 10^{-3}$, is much less severe.)

I will just mention here a different context in which radiation pressure could be important in driving jets: the "cauldron" model of Begelman and Rees (1983a,b). Here the jet contains ordinary thermal plasma and radiation; it (and its surroundings) are so optically thick that the radiation can be treated as a fluid. If the radiation pressure is sufficiently high — so that (p_{rad}/c^2) exceeds the rest mass density of the matter — then relativistic outflows can be achieved.

3. INTERACTIONS WITH CLOUDS AND THE INTERCLOUD MEDIUM

Evidence on the medium through which the jet propagates comes primarily from the broad optical emission lines. These imply clouds with $n_e \cong 10^{10}$ °K, $T \cong 10^4$ °K, and a covering factor $\gtrsim 0.1$ (though a very small volumetric filling factor). The clouds must be confined by a rarified intercloud medium: they could be in pressure balance with it, but are more probably moving supersonically through it. If the intercloud medium is at X-ray emitting temperatures, then for each r we know that

$$(n_e(r))^2 \, r^3 \lesssim 10^{69} \text{ cm}^{-3} \tag{8}$$

(the volume depending on the X-ray luminosity or limit). Its temperature is likely to be determined by a balance between Compton cooling and heating (Krolik, McKee and Tarter 1981).

For the jet to be in pressure balance with the intercloud medium,

$$P_{ext} \cong 3 \times 10^4 \, \theta^{-2} \, r_{15}^{-2} \, L_{45} \mathcal{M}^{-2} \text{ dyne cm}^{-2} , \tag{9}$$

$\mathcal{M}$ being the (relativistically generalised) Mach number. Confinement is required if $\theta < \mathcal{M}^{-1}$, and this can be supplied by external pressure only if the intercloud medium has

$$nT > 3 \times 10^{16} \, r_{15}^{-2} \, L_{45} \tag{10}$$

This is possible at $\sim 10^{18}$ cm, but is only marginally compatible with (8) at $\sim 10^{15}$ cm.

Another characteristic temperature of importance is the virial temperature. For a central object of $10^8 \, M_8$ solar masses,

$$T_{virial} \cong 3 \times 10^{10} \, r_{15}^{-1} \, M_8 \text{ °K} . \tag{11}$$

Relation (11) applies until the radius r gets so large that the dominant mass encompassed within it is no longer just the central hole but the stellar content of the galactic core: T_{virial} then (for larger r) levels of at $10^6 - 10^7$ °K, depending on the stellar velocity dispersion. The intercloud medium cannot be in quasi-static equilibrium if its temperature is below T_{virial}. If Comptonisation prevents the temperature from rising above $\sim 10^9$ °K, the intercloud medium must be dynamic rather than quasi-static for $r_{15} < 30 \, M_8$. We do not know whether the intercloud medium is undergoing chaotic infall, or is an outflowing wind, but in neither case would the argument leading to (10) be applicable.

The problem of confinement — and the constraints discussed in § 2 — would all be evaded if the power were mainly in the form of Poynting flux (only a small fraction of L_b being contributed by particle kinetic energy). This could be low frequency waves, or an axisymmetric toroidal flux spun off a central compact object. This energy could be converted into relativistic particles at the location of the VLBI components.

In this connection, it is interesting that there is a characteristic scale in galatic nuclei of $\sim 10^{19}$ M_8 cm, this being the radius at which the central mass ceases to dominate the dynamics in accordance with equation (11). Outside this radius, quasi-static hot gas can exist; at smaller radii this is problematical. It is therefore a natural scale at which a free jet encounters quasi-static gas in the galactic potential, and may be relevant to the scale of the blobs revealed by VLBI data, and to the sharp bending of jets sometimes seen on this scale.

[It has been argued from Faraday rotation considerations that the radio-emitting relativistic particles in the VLBI components are themselves a mixture of electrons and positrons. If so, the positrons must presumably have been created not "in situ" but at smaller r. Enough positrons to produce the radio emission would have been transported out along the beam even if $F_+ \cong 0.01$, the Poynting flux being used "in situ" to accelerate them from $\gamma \cong 10$ to the values $\gamma \cong 1000$ required for synchrotron radiation in the GHz band.]

In any case, the jet's ram pressure would not be sufficient to influence the trajectories of dense fast-moving clouds, still less to destroy them. Thus, the covering factor due to such clouds (along the jet axis) must definitely be < 1; otherwise the jet momentum would be isotropised before getting out to the scale relevant to VLBI observations. It would seem inevitable that some of the jet's energy is tapped (and converted into relativistic particles) on passage through the line-emitting region. If optical observations could be made with micro-arc-second resolution, they would reveal not only a central optical continuum, but also streaks of optical synchrotron radiation delineating the jet's path.

The structure of jets on scales 10^{15} - 10^{19} cm, if we could probe it in the same detail that the VLA provides for scales a million times larger, would no doubt prove just as complex — there would be entrainment of surrounding gas, bending by transverse pressure gradients, and shocks where the jet impinges on "broad line" clouds. We do not know how well collimated the jets are — there is really no evidence that θ is small on scales $< 10^{19}$ cm — but one general statement can be made. The flow patterns would not simply be a scaled down version of those seen on larger scales, because one key number — the ratio of radiative cooling times ($\propto r^2$ for a simple diverging jet) to dynamical times ($\propto r$) — is proportional to r rather than being scale-dependent. Consequently, the flows on small scales would tend to be less elastic and more dissipative: they are less likely to maintain a high internal pressure, and would dissipate more energy if bent through large angles.

4. INDUCED SCATTERING

The VLBI maps reveal brightness temperatures up to $\gtrsim 10^{11}$ °K, corresponding to $\gtrsim 20\ m_e c^2/k$. For radiation of such high intensities, the ordinary Thomson scattering cross-section is enhanced by a factor $\sim kT/m_e c^2\ \phi^2$ owing to induced effects (ϕ being the scattering angle). It is unlikely that the gas surrounding the jet has a Thomson depth $\tau_T > 1$; on the other hand, a value in the range 0.01 - 0.1 is entirely compatible with two-phase models for the medium in the broad-line-emitting region (and the observed optical polarisation would require $\tau_T \cong 0.1$ if it were due to electron scattering). Thus, the effects of induced scattering are likely to be significant.

Wilson (1982) discussed induced scattering in detail; he even proposed a model whereby intensity peaks would exhibit apparent superluminal motions along a jet-like feature in a source with a small central component varying in intensity, but with "no moving parts". This model is hard put to account for all the superluminal data we now have, but the possibility of extra effects due to induced scattering should be borne in mind in interpreting radio maps. To distinguish reliably between genuine motions and features which are merely "echoes" due to induced scattering may have to await detailed maps with similar resolution at different frequencies. The main reason why induced effects cannot offer the entire explanation of superluminal motions is that they are strongly frequency dependent — if the only data we had was at 5 GHz they would offer a plausible escape clause to those unwilling to accept bulk flows at > 0.98c.

5. CONCLUSIONS

My specific conclusions are:

(i) Relativistic beams are probably initiated on scales $\lesssim 10^{15}$ cm; but there are significant constraints on the form in which the energy is transported out to the much larger ($> 10^{19}$ cm) scales where superluminal effects are observed. If the energy were carried by electrons and positrons the beam would need to start off with a high γ_b — otherwise the required pair density is so high that most would annihilate.

(ii) The quasi-isotropic radiation field in quasars at $r \lesssim 10^{18}$cm (due to the line-emitting clouds, etc.) exerts a Compton drag which precludes high γ_b for an e^+-e^- beam (though is less serious if there is more inertia per pair).

(iii) The external medium through which these small-scale jets propagate is likely to be inhomogeneous and in a chaotic rather than stationary state: it is therefore unlikely that the beams on these scales are confined by external gas pressure.

(iv) It is a plausible inference from (i) - (iii) above, and from general theoretical considerations, that the power emerges mainly as directed Poynting flux, rather than primarily as particle kinetic energy.

(v) The jets cannot avoid some interactions with the "broad-line" clouds — some of the observed non-thermal optical continuum may result from dissipation behind shock waves in this region, rather than from the ($\lesssim 10^{15}$ cm) nucleus itself.

(vi) The scale probed by VLBI, and where the jets are often observed to bend sharply, may be the domain where T_{virial} falls to $\sim 10^6 - 10^7$ °K (eqn (11)), and the external medium is no longer dominated by the central massive object but by the ordinary potential well of the surrounding galaxy.

(vii) The intercloud medium may provide a sufficient Thomson optical depth for induced scattering to be important in modifying the appearance and variability of high-surface brightness radio components.

More generally, one must realise that the outflowing material and energy must undergo complex interactions with its surroundings before attaining the distance from the central power source at which VLBI techniques can probe it. Evidence from other wavebands, and improved theoretical understanding, are necessary before we can understand the range of scales $10^{15} - 10^{19}$ cm. Cynics may chide theorists for retreating to still smaller scales, now that the VLBI data have progressed beyond the stage of merely confirming superluminal motions, and are starting to reveal complex "weather" on milli-arc-second scales. But, on the contrary, it is surely gratifying that VLBI data can tell us about the primary energy source, and be related to observations in other wavebands.

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