PROBLEMS OF JET PHYSICS

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What have I learned about jets since the Albuquerque meeting (IAU Symposium No.97) last summer?

1. A pooer man's guide to the acceleration of jets near a black hole

There is where most of the gravitational energy is released, the funnels on the rotation axis of the accretion torus provide the right sort of geometry, and radiation is abundant. But the experts (Sikora & Wilson 1981 and references therein) never can make radiation-driven jets with Lorentz factor $\gamma >> 1$. Why? It is because, when an electron moves up through the funnel at a substantial fraction of the speed of light c, it sees as much radiation striking it from the front as from behind; acceleration then stops. Large γ are attainable only if the source of radiation subtends an angle $\lesssim 1/\gamma$ behind the source.

If the jet has a large optical depth (i.e. if its radiative viscosity is low) we can regard it as a fluid, and the above limit does not apply. But high opacity implies high particle density, and hence, for given velocity v, a large output of kinetic energy. In fact, setting funnel radius ≃ 3 Schwarzschild radii, we find

$$\left\{\frac{\text{Mean free path for photon}}{\text{Funnel radius}}\right\} \simeq \left\{\frac{\text{Eddington luminosity}}{\text{K.E. output}}\right\}\frac{v}{c}\,(\gamma-1)\,\frac{m}{m_H}$$

Thus high optical depth together with $v \simeq c$ requires either (i) particle mass $m << $ hydrogen mass m_H. But annihilation is too fast to allow a position-electron jet, unless the jet is very hot, and cyclotron radiation is likely to cool the jet, or (ii) K.E. output >> Eddington luminosity L_E. Is L_E a relevant limit? I think it is, qualitatively at any rate, if 'radiation driven' means that the radiation comes out of the walls of the funnel without dragging the walls with it.

Thus other mechanisms, such as the accretion of (matter + magnetic flux) (see Throne & Blandford 1982) are more favourable for producing

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extreme relativistic (ER) jets, with $\gamma >> 1$. Indeed, the importance of the radiation may lie in limiting the γ that can be attained!

Here I want to mention recent work by Narayan, Nityananda and Wiita (preprint). They show that the tangential force of radiation on the funnel walls can be balanced by gravity only for luminosities $\lesssim \theta^2 L_E$ (where 2θ is opening angle of funnel). If the radiation drag is allowed to move the funnel walls upward and set up convection in the accretion torus, the force diminishes (aberration again!) and luminosities of several L_E are possible, but only together with a comparable output of kinetic energy.

2. What makes jets visible?

Powerful radio galaxies (Fanaroff-Riley Class II) typically have two hot-spots, but the beams which (according to conventional wisdom) feed these hot-spots rarely appear as visible jets (6%; Laing, this session), and then only on one side. Aperture synthesis observations with high dynamic range indicate very strongly that the one-sided appearance is not solely due to relativistic beaming. Perhaps the ejection process is itself one-sided in some cases (Rudnick 1982; also Conway 1982 on 3C273), but where two fairly compact hot-spots exist it is hard to avoid the conclusion that two beams exist, one of which occasionally suffers a disease that makes it visible. We have one new and relevant piece of information: where a VLBI jet and a large-scale jet have been mapped in the same source, they point not only along the same axis but in the same direction. (Sometimes, as in 3C345, there is much curvature, but the large-scale jet is a continuation of the VLBI jet.) Most of the relevant data are scattered through IAU Symposium No.97, and Dr. Ekers has provided me with some additional examples (marked E in the list below).

VLBI and large-scale jet on same side

3C120, 3C273, 3C345 (Superluminals)
3C111, 3C286, 3C380, CygA (E)
M87, NGC315, NGC6251

Relationship complex or uncertain

3C147 (Preuss et al. 1982), 3C236

Conclusions:
(i) If we believe that large-scale jets are non-relativistic (NR), meaning $v \lesssim 0.1c$, we are forced to conclude that their "disease" originates at the scale of the VLBI jets, and that they, too, are intrinsically one-sided. Indeed, it seems likely (though it is not yet established quantitatively) that the VLBI jets could not be ER, and

some alternative explanation would have to be found for superluminal motion. For if they were ER, we should find sources in which the large-scale jet points away from us and the VLBI jet is invisible because of relativistic beaming. Such a large-scale jet without a central compact source has never been found.

(ii) A middle view is still tenable, according to which large-scale jets are mildly relativistic (MR), meaning, say, v = 0.5±0.2c, and intrinsically one-sided, while VLBI jets are relativistically beamed. That is enough to provide a strong selection effect in favour of discovering large-scale jets if they point into the hemisphere nearer to Earth.

3. Can fast jets become slow beams?

Begelman (1982) has shown that, if a jet is to remain steadily luminous as it slows down, it must be roughly sonic everywhere: see also Kahn (1982). Here I am concerned with the question whether a jet can slow without losing nearly all of its kinetic energy, so that it can still form a hot-spot at its end. To preserve $1/2\ mv^2$ as velocity v decreases requires increasing mass m. However, mere entrainment of mass turns K.E. into heat; re-conversion into K.E. requires more momentum, which can only be supplied if the jet is confined by gradually diverging walls that exert a net forward force. Applying only Newton's second law and the condition Δ(K.E.) $\geq$ 0 one finds

$$-\frac{\Delta v}{v} \leq -\frac{1}{\Gamma M^2}\frac{\Delta P}{P}$$

where P = pressure, M = Mach number and $\Gamma = C_p/C_v$. Thus the velocity varies as a power < $1/\Gamma M^2$ of the pressure and, though the pressure probably falls by many orders of magnitude between 10 pc and 100 kpc, the velocity falls very little except where the Mach number is reasonably small, and the jet therefore requires a substantial confining pressure. (The calculation is non-relativistic so far, but so long as $(\gamma - 1) \gtrsim 1$ much of the energy is kinetic energy by definition, so no difficulty arises.)

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