JETS AND TRANSIENTS

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1. Introduction

I have been asked to provide some general introduction to the topic of jets and high energy transients. I have chosen to do this by asking seven questions that seem to be timely following recent observational and theoretical developments, the most important of which may be the growing realization that the extragalactic- massive black hole and Galactic-stellar mass black hole manifestations of these phenomena provide two complementary ways of viewing a common physical mechanism. I have also chosen to illustrate these questions using one specific source in each case. The page limits prevent me from giving the answers. They also prohibit my even attempting to give a skeletal bibliography over so large a field. Fortunately almost all of these topics will be covered in greater depth during this meeting.

2. What is the State of the Gas?

Although we may be intensely interested in what goes on around the black hole, most of what we see from AGN and XRB is secondary, reprocessed radiation. The problem is epitomized by NGC 1068 (Gallimore 1997). The central action is widely believed to be obscured from view by an orbiting torus of gas. This means that broad emission lines are only seen in polarized, scattered radiation and the X-rays are highly attenutated. The torus contains dusty molecular gas and is associated with OH and H_2O masers. The observed velocities suggest a black hole mass of $\sim 1.5 \times 10^7$ $M_\odot$ though the kinematics is not simply Keplerian. The bolometric luminosity is at least $\sim 10^{44}$ erg s^{-1}, not a lot short of the Eddington limit. In addition we see high latitude gas is illuminated by an ionization cone (from which we are excluded), suggesting that we have seriously underestimated the luminosity. In addition radio observations reveal an inner disk of ionized gas and outflowing radio jets traced well out of the nucleus.

A pre-requisite for understanding the accretion process is to understand the disposition of the gas around the nucleus, whether it is inflowing or being blown out and whether it is molecular, atomic or ionized. In general we want to know how much of the gas is reprocessed and to understand its dynamical intereaction with the jets. We need to understand how its orbital angular momentum evolves with radius so as to determine whether the jet axis is fixed by the outer disk or the spacetime geometry defined by the supposedly spinning central black hole.

3. What is the Power Supply - the Hole or the Disk?

If we turn to another AGN, M87, (Meisenheimer & Röser 1997)with a measured hole mass, $\sim 3 \times 10^9$ $M_\odot$, then we are forced to inquire about the global energetics. In round numbers the observed power from the nucleus appears to be $\sim 10^{42}$ erg s^{-1}, that from the jet $\sim 10^{43}$erg s^{-1}, whereas the Eddington uminosity is $\sim 4 \times 10^{47}$ erg s^{-1}. The rate of gas supply to the nucleus can be estimated in two ways, from the Bondi formula for quasi-spherical accretion, which gives a rate $\sim 10^{25}$ g s^{-1}, and from the mass dropping out of the cooling flow which is reported to be a

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hundred times larger. At face value, M87 has all that it needs to be a very powerful quasar and yet is actually very dim.

One answer is that the accretion rate is indeed very high, the viscosity large and most of the liberated internal energy is swallowed by the hole. This requires that that the electrons are not heated efficiently relative to the ions. An alternative possibility is that accretion is inhibited far from the black hole. The gas may be heated radiatively so that it is lost in a thermally driven wind or driven away from the hole by magnetic stress. Either way, it appears that the majority of the AGN power is carried by the jets and these now appear to be derived from close to the black hole (strong, superluminal motion is seen in Knot A and collimation is apparent within $\sim 60m$).

Now, the gravitational mass m of a black hole, spinning with angular velocity Ω, can be written in the form $m = m_0(1-\beta^2)^{-1/2}$, where m_0 is the irreducible mass and $\beta = 2\Omega m_0/c$. This means that up to 29 percent of its rest mass is, in principle, usable. Furthermore, this spin energy may be extractable using electromagnetic field. I believe that it is possible, under some circumstances, for more power to be released by the hole than the acccreting gas. We have to understand theoretically if this is really true and observationally when it might be happening.

4. Are Jets Collimated by Large Scale Field?

Jets were originally an explanation for the formation of the powerful, extragalactic double radio sources, a fairly rare pathology among AGN. Now, we see jets and bipolar outflows as a regular, concomitant of the accretion process in Galactic and extragalactic sources. When looked at the scales on which they can be resolved, their most impressive feature is their collimation. A good example is Cygnus A (Carilli & Harris 1996), where the jets appear to carry a power of $\sim 10^{45}$ erg s^{-1} at relativistic speed and the jet maintains its integrity as it expands from 0.2 pc to nearly 100 kpc. A simple, equipartition estimate applied to the inner jet reveals that its internal pressure significantly exceeds the upper bound (on the basis of X-ray observations) on the external pressure. The most natural and common inference is that jets, in general, are confined by hydromagnetic stress.

It has generally been argued that, if this is indeed what is happening, the field is more likely to be toroidal rather than poloidal, because the pressure of the former is likley to decay with radius $\propto r^{-2}$, whereas the latter will decay as $\propto r^{-4}$. However, jets confined by toroidal field alone are more likely to be unstable to be pinching and kinking modes (although this is mitigated somewhat when the bulk velocity is highly super-Alfvénic). Perhaps, as a jet propagates out of the nucleus, the confining toroidal field is entrained by the flow and is able to reconnect. In this way the jet can gradually change from being magnetically dominated to being particle dominated. The brightest features are less severely overpressured on larger scales and may well be transient compression waves and shock fronts. In principle, toroidal field can be detected by Faraday rotation or circular polarization observations.

There may be a new feature to the jet collimation problem. In the laboratory, high Mach number jets propagating in gas of uniform density are generally decelerated after they have propagated a distance given roughly by the product of their Mach number and their diameter. It has long been recognized that extragalacic jets propagate in region where the external density and pressure decline with distance and that this may account for their unusual persistence, through nearly six decades in radius in extreme cases. However, we know that the jets from some binary X-ray sources and protostars persist for tens of parsecs in media that ought to become fairly uniform. Perhaps there is some novel feature responsible for the confinement in these cases.

5. How Strongly Beamed is the Emission?

Relativistic beaming was predicted to avoid the inverse Compton limit $T_B < 10^{12}$ K. Galaxies like 3C273 (Cohen & Kellerman 1996) are found to contain features that move across the sky with an apparent speed $\sim \gamma c \sim 10c$ consistent with being a shock front in a collimated jet approaching us with true speed $\sim 0.995c$ and an inclination $\sim 5°$. At the lowest level of description, the direct brightness temperature will be boosted by a factor $O(\gamma)$ and therefore should not exceed $\sim 10^{13}$ K.

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However the brightness temperature computed by using the source variability timescale to estiamte the source size, can be boosted by a factor $O(\gamma^3)$. The flux ratio of the approaching to the receding jet can be as large as $\sim 8\gamma^6$ which is sufficient to account for the observation of one-sided jets, even in 3C273.

However, radio astronomers have been measuring rapid (intraday) high frequency variation in several sourves and these give variability brightness temperature that can be as large as $\sim 10^{21}$ K. In order to comply with the inverse Compton limit, the Lorentz factors would have to be at least as large as $\gamma \sim 10^3$, perhaps not unthinkable given the situation with γ-ray bursts which require comparable Lorentz factors. However, radio jets of such high Lorentz factor are radiatively quite inefficient if the emission is due to the synchrotron process.

Now it is possible that the variations are due to refractive scintillation. However, this requires the true brightness temperature to exceed $\sim 5 \times 10^{14}$ K and so we are not a lot better off. Alternatively, a coherent emission process may be at work. This causes a problem if the emission comes from close to the black hole because it is hard to see how the radiation escapes without suffering catastrophic induced Compton or stimulated Raman scattering. Perhaps the best compromise is for coherent emission to originate behind strong, relativistic shocks propagating in the jet.

6. What Dynamics Determines the Jet Velocity?

We still do not know what factors are responsible for fixing jet speeds. The most interesting case is SS433 (Margon 1985), where the measured jet speed has a constant value of $0.26c$, puzzlingly small in comparison with the speeds inferred for extragalactic sources. In addition the jet axis undergoes a regular, 164 d precession. There is still no widely accepted explanation for the value of the jet velocity in this most remarkable of sources. Perhaps a clue can be found in the observation that, as with other examples, the jet power appears to be much greater than the Eddington limit for the central black hole (presuming that it is a black hole, which is still not proven).

There are also strong clues to be found in the increasingly striking observations of protostellar jets where the jet speeds are characteristic of the stellar escape velocities and it is assuredly not necessary to have a black hole and a low radiative efficiency. (Note, however, that if extracting power from the spin of the hole is an essential part of the jet formation mechanism in extragalactic jets, drawing mechanical energy from the boundary layer may be its functional equivalent in the case of a protostar.

7. Are Jets Electromagnetic, Leptonic or Baryonic?

We still do not know the composition of jets, or indeed if this matters. The quasar 3C279 was one of the first "superluminal" radio sources to be discovered and kinematic studies have shown that there appears to be a jet approaching us moving with a Lorentz factor $\gamma \sim 10$ (Hartmann et al 1996). It should therefore not have been a surprize when it turned out to be the most prominent of the extragalactic γ-ray sources observed by EGRET at ~ 1 GeV energies. It has an inferred power of $\sim 10^{48}\Delta\Omega$ erg s^{-1}, where $\Delta\Omega$ is the solid angle filled by the jets, measured in steradians. It is also rapidly variable over days. (15 minute variability is reported, at TeV energies, from MKN 421). The jet is clearly originally a high energy phenomenon and the radio emission is only a diagnostic of what the flow becomes.

It is mostly agreed that these high energy γ-rays are made by inverse Compton scattering of softer ultraviolet and X-ray photons by relativistic electrons. We also know that this cannot happen too close to the central black hole; the opacity to pair production would be too high. This defines a pair photosphere which is the (energy-dependent) surface where the pair production, escape optical depth falls to unity. If the γ-rays are produced near the photosphere, then the jet is likely to be in the form of a electron-positron pair flow. Conversely, if the γ-rays come from greater radii, the jets can be predominantly electron-ion in character. Pure, electron-positron jets can only exist at intermediate radii. At small radii, radiation drag is catastrophic and there must be some alternative carrier of momentum. The prime candiate is electromagnetic field, (just as happens with the Crab pulsar). At large radii, entrainment probably guarantees that the outflow is an ionic plasma.

8. Are QPO's due to Disk Dynamics?

Recent observations of the two Galactic superluminal sources, GRS 1915+105 and GRO J 1655-40 (Greiner, Morgan & Remillard 1996), are almost certainly bringing the nature of the disk-hole-jet connection into sharper focus. (Observing Galactic sources gives much more rapid gratification than waiting for extragalactic source to vary.) The former source shows the most remarkable quasi-periodic variability on timescales from 16 ms to 40 minutes (and perhaps even longer). It also demonstrates that the X-rays have a non-thermal origin and that there is an strong dynamical connection between the inner disk and the outer jet (revealed by correlated and delayed variation) between the X-rays, the infrared and the radio emission. The latter provides the most detailed picture of how the jet behaves with strong outbursts and precession.

We are clearly coming to terms with general disk inflow and jet outflow as "cataclysmically variable", and not necessarily well described by the axisymmetric stationary and occasionally linearly unstable configurations, usually analyzed by theorists. The lessons that we have all been learning over the past two decades in non-linear dynamics may find ready application in these systems.

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