What ignites optical jets?* †

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The properties of radio galaxies and quasars with and without optical or X-ray jets are compared. The majority of jets from which high-frequency emission has been detected so far (13 with optical emission, 11 with X-rays, 13 with both) are associated with the most powerful radio sources at any given redshift. It is found that optical/X-ray jet sources are more strongly beamed than the average population of extragalactic radio sources. This suggests that the detection or non-detection of optical emission from jets has so far been dominated by surface brightness selection effects, not by jet physics. It implies that optical jets are much more common than is currently appreciated.

1. Introduction

In the standard model for Active Galactic Nuclei (AGN), jets transfer mass, energy (kinetic and electromagnetic) and momentum from the central object into the surrounding medium. Liu and Zhang (2002) recently compiled a list of radio jets from the literature. Adopting the definition from Bridle and Perley (1984), they list 925 jets associated with 661 radio sources. Most of the jets have been identified by their radio synchrotron emission. Only a few of them also show optical synchrotron emission. Based on the most recent list of optical jets by Scarpa and Urry (2002) and the list of X-ray jets by Harris and Krawczynski (2002), I have compiled a list of 26 jets from 26 sources which have optical emission associated with them[3].

Only a few optical jets have been studied in detail, most notably M87 (e.g., Meisenheimer et al., 1996; Perlman et al., 1999, 2001) and, in fewer bandpasses, 3C 273 (e.g., Röser and Meisenheimer, 1991; Jester, 2001, and references therein), but they have hardly been considered as a class of objects. The small number of known optical jets suggests the conclusion that they are very rare objects. This would, in fact, be expected from synchrotron physics: the magnetic fields expected in jets are of order of a few nanoTesla. This means that the loss timescales for electrons emitting optical synchrotron radiation are of order 1000 years or shorter, while typical arcsecond-scale jets have lengths from a few up to a few hundred kiloparsec. Thus, it seems natural that the frequency ν_c at which a jet's power-law spectrum cuts off lies below the optical wavelength region in most cases.

However, in most jets where optical emission has been observed, it extends over scales much larger than the lifetimes of "optical" electrons would permit. Scarpa and Urry (2002) showed that *on average*, optical jets are sufficiently relativistic to remove the lifetime discrepancy by time dilation, without the need for reacceleration of particles within the jets (before this, Sparks et al., 1995, had already shown that all optical jets known then are probably beamed). Still, at least in 3C 273's jet in-situ acceleration is necessary to explain the observed optical synchrotron emission, in particular because very strong beaming increases the energy loss by inverse Compton scattering of microwave background photons (Jester et al., 2001). Moreover, the X-rays from many jets are explained as synchrotron emission as well (Harris and Krawczynski, 2002) – with

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[3]The full list with references is available online at http://home.fnal.gov/~jester/optjets and will be contained in a forthcoming publication. The following optical jets are not in Scarpa and Urry (2002): 3C 31, PKS 0637−752, B2 0755+37, PKS 1136−135, PKS 1150+497, 3C 279, 3C 293, PKS 1354+195, 3C 303, B2 1553+254, B2 1658+30A, 3C 380.

much shorter loss timescales than in the optical, and correspondingly a more severe lifetime discrepancy which is harder to remedy by relativistic effects.

It appears thus that the number of optical and X-ray jets is small because some special physical conditions are necessary either to switch on the extended acceleration mechanism (whose nature remains elusive), or to accelerate the corresponding electrons near the AGN's core and allow their escape to kiloparsec scales. However, in direct contradiction to this, Capetti et al. (2000) noted that the detection rate of optical jets in the B2 radio survey implies they are "not particularly rare".

Here I make an attempt to find out what the required physical conditions are, and indeed whether they are special. Like Sparks et al. (1995), I find that beaming plays a role, and that more work is necessary before we can get beyond the observer-dependent beaming to the intrinsic physical conditions.[4]

2. A case study: 3C 273

In this place, I only briefly mention an idea which could help to explain the onset of bright high-frequency emission in the jet in 3C 273, where beaming alone cannot explain the observed optical emission. This jet has a divided appearance, with a continuous radio jet extending out to $21''.4$ projected distance from the core, but with bright optical and X-ray emission only beyond $12''$ from the core. In Jester & Krause (ApJ, in preparation), we suggest that the jet may be lit up by making a transition from being overdense to underdense, with a strong shock forming near the transition region. We show a 2.5D hydrodynamical simulation supporting this suggestion. Full details will be contained in our forthcoming publication.

3. Optical jets: a beaming selection effect?

Synchrotron radio sources are usually assumed to have approximately power-law spectra, with a steep high-energy cutoff at some frequency ν_c above which there is no significant emission. An objective definition of an "optical" jet would require a cutoff frequency beyond the near-infrared. A statistically complete survey for optical jets would include a surface brightness limit. Such a survey does not exist. I have therefore divided the radio jet list by Liu and Zhang (2002) into subsets: the 26 jets with detected optical emission, and the remainder as "radio-only" jets. This is in effect a qualitative definition of an "optical" jet.

As a third class, I consider X-ray jets (this class consists entirely of objects already included in the previous two classes). Seven radio jets show X-ray emission, but no optical, and thirteen jets have both optical and X-ray emission. I am not considering optical or X-ray emission from hot spots, only from the jet beams themselves.

I first consider whether the presence of optical emission from the jet is related to the core's radio power. Figure 1 shows that at fixed redshift, nearly all optical jets are associated with radio sources which are more powerful than the median at that redshift. The same is true for X-ray jets. Conversely, among the sources at a fixed radio power, only the lower-redshift sources have optical or X-ray emission. Thus, there is no intrinsic correlation between core power and the presence of high-frequency emission.

The histograms in Figure 1 show that optical and X-ray jets are more likely to be 1-sided than an average radio jet, although this arises in part from the correlation between sidedness and jet power (Liu and Zhang, 2002). Jet sidedness is of course an indicator for relativistic beaming.

Another beaming indicator is the core prominence ratio R, the ratio of core power (affected strongly by beaming) to extended power (not affected strongly) at a fixed rest-frame frequency (e.g., Laing et al., 1999). Figure 2 shows the core prominence ratio of the three classes of jets as function of extended power. I have computed R from the observed-frame values for core power at 5 GHz and total power at 1.4 GHz listed by Liu and Zhang (2002), assuming a flat core spectrum and $f_\nu \propto \nu^{-1}$ for the extended component.

Scarpa and Urry (2002) have argued that the emission from optical jets is indeed on average

[4] The cosmology is that used by Liu and Zhang (2002): $H_0 = 100\,\mathrm{km/s/Mpc}$, $q_0 = 0.5$.

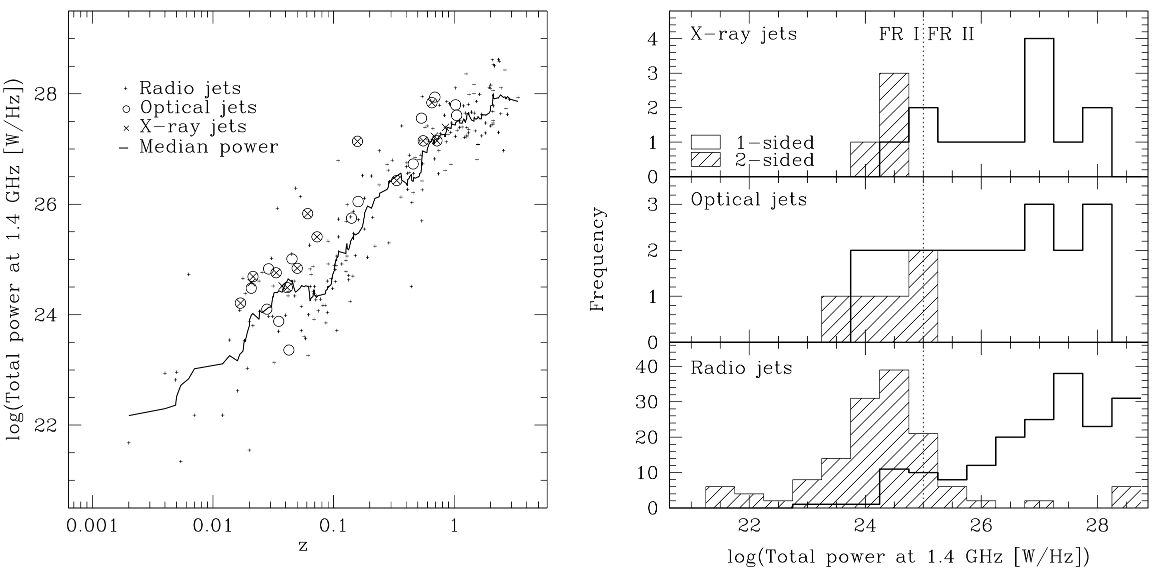

Figure 1. *Left:* Core power as function of redshift for extragalactic radio sources with jets (data from Liu and Zhang, 2002). The median radio power for galaxies without optical jets (solid line) was determined at each redshift by boxcar-smoothing the radio power over the 15 nearest neighbours in redshift. *Right:* Histogram of radio powers for sources with jets, divided by jet sidedness ("1-sided" jets are (roughly) those in which the jet:counterjet ratio exceeds 4, while all other jets are labeled as "2-sided"). The dotted line shows fiducial power separating FRI and FRII sources. Note that not all sources from the Hubble diagram on the left have a sidedness determined.

beamed up. But Figures 1 and 2 suggest a stronger statement: First, all sources with detected radio jets are beamed. Secondly and more importantly, optical and X-ray jets are *more strongly* beamed than "radio-only" jets. By comparison of the jet points with the median relation for all radio sources (dashed line in Fig. 2), sources with radio jets in turn seem more strongly beamed than the radio source population as a whole. However, in interpreting this result, one should remember the inhomogeneity of the jet data set and the relatively crude spectral corrections.

Since the X-ray emission of some jets is explained as beamed inverse Compton scattering of microwave background photons (see the overview by Harris and Krawczynski, 2002), it is expected to find strong beaming for some of the X-ray jets. However, optical emission is usually shown or assumed to be synchrotron emission (with the possible exception of the ultraviolet excess observed from 3C 273's jet; Jester et al., 2002), without reference to beaming. While there may be a physical connection between the jet's bulk Lorentz factor and the intrinsic optical brightness (because more kinetic energy is available to be converted into relativistic particles, for example), I propose here that the sample of optical jets detected so far has overall no special physical significance, but they have only been detected because their intrinsic surface brightness has been beamed up sufficiently.

Just before the time of this writing, a paper appeared as preprint which shows that exactly this surface brightness selection effect can account for the optical non-detection of all but two jets in HST imaging of 57 sources from the B2 sample (Parma et al., 2003). If this holds for all other

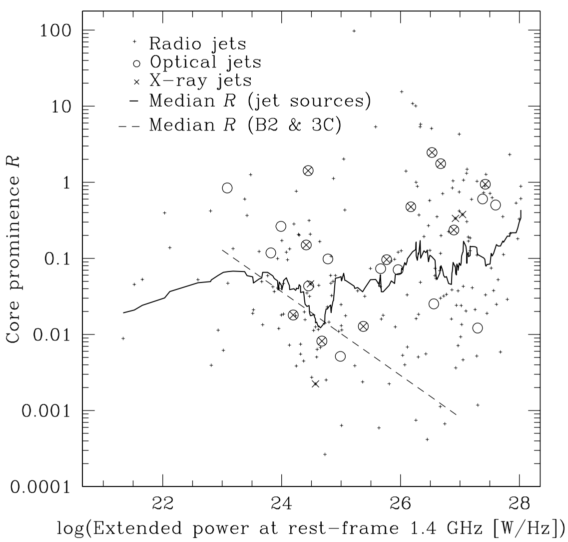

Figure 2. Core prominence, R, against extended power at rest-frame 1.4 GHz, $P_{\mathrm{e}}^{(1.4)}$. The solid line is the median core prominence at each radio power and is obtained by boxcar-smoothing over 19 neighbouring radio sources in extended power. The dashed line shows the median relation found by de Ruiter et al. (1990) for the low-power B2 sample together with the nearby sources from the 3C catalogue (i.e., including both FRI and FRII sources): $\log R_{\mathrm{m}} = -0.55 \log P_{\mathrm{e}}^{(1.4)} + 11.76$. It is plotted over the range in power for which it has been determined by de Ruiter et al. (1990).

searches, it implies that optical jets are much more common in all extragalactic radio sources than has been appreciated so far, and they have not been detected in significant numbers simply because they have not been looked for with sufficient surface brightness sensitivity.

4. Conclusions: Finding more optical jets

The present comparison of the radio properties of sources with detected optical or X-ray jets to those with "radio-only" jets has not brought to light any connection between intrinsic physical properties and the presence of optical or X-ray emission. Instead, it is found that optical jets are more strongly beamed on average than other radio jets are. I therefore suggest that the entire sample of presently known optical jets is determined mainly by surface brightness selection effects. Like Parma et al. (2003) have done for the B2 sample, this suggestion has to be tested by comparing the optical surface brightness expected from an extrapolation of radio maps with a suitable power law ($f_\nu \propto \nu^{-0.7}$ represents most jet spectra well) to the surface brightness limits of available optical observations. For those jets without suitably deep observations, the most efficient search method will employ observations in the near-infrared. In this way, jets with cutoffs just below the optical are still detectable. Positive detections will be followed up by observations in a second bandpass to determine the spectral index, and hence the detectability at higher frequencies. Only with a firm sample of detections *and* non-detections can we analyse the dependence of the jet's synchrotron cutoff frequency ν_{c} on other observables and thus address the question of what ignites optical jets.

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