Revealing the Energetics and Structure of AGN Jets

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Abstract.

Until very recently, few constraints existed on the physics of jets, even though they represent the first known evidence of mass outflow in AGN. This has begun to change with HST and Chandra observations, which allow us to observe short-lived, dynamic features, and compare their spectra and morphology to those of longer-lived particles seen in the radio. We examine HST and Chandra observations of M87 and 3C273 which reveal that these two prototype objects seem radically different.

1. Introduction

Collimated jets occur in many settings, including galactic nuclei, binary star systems, and star formation. AGN jets are relativistic flows composed of high-energy particles and magnetic fields, which emit synchrotron radiation in the optical and radio. Jets were the first AGN outflows observed, discovered by Curtis (1918), who noticed a ‘curious, straight ray’ emanating from M87.

Prior to the launch of HST, optical emissions had been observed from two AGN jets: M87 and 3C273 (Schmidt 1963). ROSAT and Einstein observed X-ray emissions from the jets and/or lobes of these (Schreier et al. 1982, Stern & Harris 1986) plus four others: Cen A (Burns et al. 1983), Cygnus A (Harris et al. 1994), 3C390.3 (Harris et al. 1998) and 3C120 (Harris et al. 1999). HST observations, particularly the 3CR Snapshot Survey (Martel et al. 1999), have drastically increased the number of known X-ray or optical jets to about 20, representing a fair cross-section of radio-loud AGN properties.

Because of the featureless nature of synchrotron spectra, the jump from morphology to physics is large for jets. Some progress has been made through numerical modeling and multi-frequency radio mapping, but this elucidates only a small part of the energy spectrum, and details can be obscured by the long particle lifetimes ($10^5-6$ yr). Due to their short radiative lifetimes, optical and X-ray synchrotron emitters ($\sim 1-100$ yr), represent much more dynamic characteristics. Thus to obtain the tightest constraints, multiband data are required.

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2. An issue of stratification

One of the surprises provided by HST observations was that the optical and radio morphologies of jets can be quite different. For example, in 3C273 the optical jet appears much narrower than seen in the radio, with a twisted, even ‘braided’ morphology (Röser et al. 1997). And in M87, there is a large-scale correspondence of features, but detailed comparison reveals a narrower, knottier jet in the optical (Sparks et al. 1996). Therefore it should not have been a surprise when the first Chandra data revealed yet more differences. For example, in Cen A, the X-ray and radio maxima of several knots appear offset by up to an arcsecond (Kraft et al. 2000). What do these represent: different physical conditions, different emission mechanisms, or both?

Perlman et al. (1999) proposed that the radio-optical differences in the M87 jet could be explained by stratification. What led to this conclusion was HST and VLA polarimetric images, which revealed large differences in knots, where the magnetic field vectors seen in the optical (but not radio) become perpendicular to the jet upstream of flux maxima, followed by sharp decreases in optical polarization at flux maxima (their Figures 3-6). Under the Perlman et al. model, high energy electrons are concentrated along the axis and in knots, where the magnetic field is compressed by shocks, while the sheath is dominated by lower-energy particles, with a more static, parallel magnetic field.

Naively, the idea of a stratified jet is not novel: in a fire hose, the fastest part of the flow is in the center. In fact, a decade ago some authors proposed ‘two-fluid’ jet models (cf. Sol, these proceedings). Stratification has far-reaching implications. For example, instabilities need not involve all components of the jet flow. Moreover, a compressed, perpendicular magnetic field in knot regions is a recipe for particle acceleration. It instructive to look at the X-ray and optical flux and spectral morphology, where several of these features should show up.

3. Spectral and X-ray Morphology of the M87 and 3C273 Jets

M87 (d=16 Mpc) and 3C273 (z=0.158) are the prototype jets, having both the largest angular extents and high surface brightness. They are very different objects, differing by a factor 100 in luminosity and jet power, and by a factor 30 in physical jet length. One might therefore expect a detailed comparison to show interesting differences.

Looking first at Figure 1, we can see that in the M87 jet, there is an excellent overall correlation between optical flux and optical spectral index $\alpha_o (F_\nu \propto \nu^{\alpha})$: in high surface brightness regions, one sees flatter spectra. Near knot maxima one sees exactly the kind of hardening, followed by softening, that one would expect if particle acceleration is occurring in the knots. Interestingly, the optical and radio-optical ($\alpha_{ro}$) spectral indices do not vary together. In each knot region in the inner jet, we observe $\alpha_o$ either leading or lagging $\alpha_{ro}$. One can understand this in the context of particle acceleration (Kirk et al. 1999): if the acceleration timescale is much less than the cooling timescale for optical synchrotron emitters, one expects $\alpha_o$ to lead $\alpha_{ro}$; however if the acceleration and cooling timescales are of similar order, one would expect $\alpha_{ro}$ to lead. A different situation is seen...
Figure 1. Radio (VLA, 2cm, top), optical (HST, I band, second panel), X-ray (Chandra, third panel), $\alpha_o$ (fourth panel) and $\alpha_{ro}$ (bottom) images of the M87 jet. The Chandra ACIS+HETG image was adaptively smoothed. Contours represent (3, 5, 8, 16, 32, 64, 128, 256...) $\times$ rms noise. Note the strong correlation between optical flux and spectral index. This, along with polarimetric imaging, strongly argues for energetic stratification. The X-ray and optical peaks of most knots are located in the same places, but there are two optically faint regions where X-ray peaks are seen, in the D-E and E-F transitions.
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in the outer jet, where there is an anticorrelation between \( \alpha_o \) and \( \alpha_{ro} \). This might indicate that the jet core has a steeper injection index than the sheath.

X-ray emission is seen from all regions of the M87 jet, and several optical and X-ray knot maxima are located at the same \( \theta_{nuc} \), e.g., HST-1 (nuclear distance \( \theta_{nuc} = 1'' \)), A (\( \theta_{nuc} = 12'' \)) and C (\( \theta_{nuc} = 18'' \)). Knot A’s X-ray and optical maxima are at the same \( \theta_{nuc} \), not displaced by 0.5", as had been claimed by Neumann et al. (1997) and Böhringer et al. (2000) The most likely explanation is the unexpected brightness of HST-1, which Chandra only partially resolves from the core, and is hopelessly blended with it in ROSAT and XMM images. There are, however, significant morphological differences. In knot E (\( \theta_{nuc} = 5 - 6'' \), the X-ray bright region begins 1" upstream of the optical peak, in an optically faint region. Also, in knot F (\( \theta_{nuc} = 8'' \)), the X-ray bright region begins 0.6" upstream of the optically bright region, and the maxima are displaced. The difference in knot D (\( \theta_{nuc} = 2.5'' - 4'' \)) is more subtle: the decline in X-ray flux following maximum is much steeper than in the optical.

The X-ray spectral indices and broadband SEDs indicate that the X-ray emissions of the M87 jet are due to synchrotron radiation (Böhringer et al. 2001, Marshall et al. 2001a). Since the lifetimes of X-ray synchrotron emitting electrons are only a few years, particle acceleration is required. Spectral fits and variability timescales constrain these regions to be a small fraction of the volume of each knot (Harris et al. 1997, Perlman et al. 2001, Marshall et al. 2001).

Turning to Figure 2, we see that in the 3C273 jet there is no correlation between the optical flux and spectral index. Instead, there is a gradual steepening in \( \alpha_o \) with \( \theta_{nuc} \), overlaid with small variations, e.g., flattenings in the A-B1, B1-B2 and C1-C2 transitions. Thus physical conditions in the 3C273 jet change remarkably smoothly over scales of many kiloparsecs. A detailed spectral index map also reveals evidence of superposed emission regions in some knots (Jester et al. 2001a). This is very different from the M87 jet, illustrated above.

Jester et al. (2001a) note that the consistency of the ground and HST-observed runs of \( \alpha_o \), the gradualness of the spectral changes and the lack of correlation between optical flux and \( \alpha_o \), are consistent with no radiative cooling over scales of many kiloparsecs. But optical synchrotron emitting particles have lifetimes \( \sim \) hundreds of years. Jester et al. (2001a) conclude that the only way to escape this paradox is to have continuous reacceleration, throughout the jet’s length. This is not inconsistent with stratification, but it is very different from what we see in M87. Optical polarimetry would be invaluable to examine these issues further. Unfortunately the current HST polarimetry (Thomson et al. 1993) is too low signal to noise; reobservation is required.

Comparing optical and X-ray images of 3C273 (Marshall et al. 2001b, Sambruna et al. 2001), one sees further differences. Knot A is by far the most powerful in the X-rays, whereas the optical fluxes of all knots are within a factor of two, and the radio maximum occurs in knot H. In addition, the X-ray and optical peaks in knot B appear offset, and no X-ray emission is seen in knot H2. There is debate over the X-ray emission mechanism for knot A: Marshall et al. (2001b) and Röser et al. (2000) favor synchrotron radiation, while Sambruna et al. (2001) claim that Comptonization is required. But these authors agree that the X-ray emissions of the other knots is due to Comptonization of CMB photons. Deeper observations are needed to distinguish between mechanisms.
Figure 2. Optical (Jester et al. 2001b, top) and X-ray emissions (bottom) of the 3C273 jet. The top panel shows runs of $\alpha_o$ (points and dashed curve at top) and optical flux (solid curve). The Chandra image is adaptively smoothed. By contrast to M87, in the 3C273 jet optical flux and $\alpha_o$ are uncorrelated. Also, the X-ray and optical maxima of knot B are offset by $\sim 0.5''$ and X-ray emission is not seen at $\theta_{nuc} \gtrsim 21''$. This implies different physics than seen in the M87 jet.

4. Discussion

There are significant differences between the observed morphologies of the M87 and 3C273 jet, which probably translate to differences in structure and physics. Unfortunately, not all of the observations are in place even for these objects. For 3C273, better HST polarimetry is required, and several more bands of deep optical imaging would be very helpful to pin down the $\alpha_o$ map better (compare the error bars in the runs of $\alpha_o$ in Figures 1 and 2). For M87, the magnetic and energetic structures are better constrained, but there are other issues, for example the observed superluminal motion in several knots (Biretta et al. 1999a,b) and the evolution of physical conditions in those components.

We are only scratching the surface of the range of properties in jets. Many new observations are needed. Through cycle 9, four of the twelve known jets brighter than 20 mag/arcsec$^2$ have only snapshot HST observations, and four more have only shallow exposures and poor spectral coverage. Moreover, through Cycle 9, polarimetry had been done only for M87 and 3C273 (3C264 and 3C78 are scheduled for Cycle 10). Chandra is doing somewhat better; deep observations have been obtained or scheduled for 7 of the 12 brightest optical jets.
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