X-ray Variability and Emission Process of the Radio Jet in M87

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Abstract

We monitored the M87 jet with the ACIS-S detector on Chandra with 5 observations between 2002 Jan and 2002 Jul. Our goal was to determine the presence and degree of variability in morphology, intensity, and spectral parameters. We find strong variability of the core and HST-1, the knot lying 0.8″ from the core. These observations were designed to constrain the X-ray emission process: whereas synchrotron emission would necessitate the presence of extremely high energy electrons with a halflive of a few years or less, inverse Compton emission from a relativistic jet would arise from low energy electrons with very long halflives. Currently, all indications point to a synchrotron process for the X-ray emission from the M87 jet. We give key parameters for a “modest beaming” synchrotron model.

Key words: M87, relativistic jets, X-ray variability

1 Introduction

Although there is general agreement that X-ray emission from radio jets arises from non-thermal processes, both synchrotron emission and inverse Compton (IC) emission are indicated for different, and occasionally the same, radio features (Celotti et al. 2001, Marshall et al. 2001, Sambruna et al. 2001). Here we present strong evidence that synchrotron emission is responsible for the X-ray emission from the M87 jet and demonstrate a reasonable combination of source parameters for HST-1, the jet feature lying 0.8″ from the nucleus.

We take the distance to M87 to be 16 Mpc so that one arcsec = 77pc. We use the normal convention for spectral index: flux density, S ∝ ν^−α.
2 Data Processing and Results

We used a 1/8th subarray on the back illuminated ACIS-S3 chip with 0.4s readout to mitigate pileup; the same configuration used for a 12ks archival observation of 2000Jul. A 'standard' reduction system, based on the CIAO threads, was developed to ensure that each dataset was processed identically. We believe that the key to reliable photometry for closely spaced features is to remove the pixel randomization and re-grid to 1/10th pixel. This process recovers the true resolution of the Chandra Observatory. The event files were then binned and filtered into three energy bands: soft = 0.2-0.75keV; medium = 0.75-2 keV; and hard = 2-6 keV. The bands were chosen to minimize the change in effective area across each band, although this was not possible for the soft band. We then created corresponding exposure maps and divided the images by these to obtain flux maps. By testing on a fixed area of hot cluster gas, we recovered the quantum efficiency (QE) degradation of the ACIS CCD. Multiplying each band map by $h\nu$ of the mean energy plus the correction factor for QE, we obtained flux maps comparable to the 2000 observation.

The basic results for the core and HST-1 are shown in fig. 1 and strong intensity variability can be seen. Using small circular apertures for the core, knot A, and HST-1, we obtained the relative fluxes shown in figure 2. HST-1 increased by a factor of two in the last 116 days covered by our observations. The light travel time for this interval is 0.1pc which may be compared with our inherent resolution of order $0.3''$ or 23pc at the distance of M87.

3 HST-1

We take our variability data of HST-1 to support the synchrotron emission model since when the flux is decreasing, there is a larger percentage drop in the hard band than in the medium or soft bands, and the flux decrease is consistent with half-lives of order a year rather than a value of order 10,000 years corresponding to the low energy electrons which would produce inverse Compton (IC) X-rays.

We used a single power law to fit the optical (Perlman et al. 2001) and X-ray flux densities of HST-1 from $\nu_1 = 10^9$ Hz to $\nu_2 = 10^{18}$ Hz with $\alpha = 0.68$. With this spectrum, we then derived synchrotron parameters based on the usual equipartition assumptions (Pacholczyk, 1970) for two alternative source sizes: $r=0.3''$ and a radius corresponding to the light travel time of 116 days. For each choice, we examined parameters for beaming factors, $\delta$ ranging from 1 to 16. For those parameters requiring a value of the bulk relativistic velocity, we assumed $\Gamma = \delta$. 

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Fig. 1. The core and HST-1: (A) is the archival observation of 2000Jul and our 5 monitoring observations of 2002 follow. The contours increase by factors of two with the lowest contour level being $2 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ per pixel in the 0.2 to 6 keV band. The data were regridded to a pixel size of 0.0492$''$; and a Gaussian smoothing function of FWHM=0.25$''$ was applied.

Fig. 2. Hard band lightcurves for the M87 core, HST-1, and knot A. The observation at the left is from 2000Jul; those to the right from the 2002 season. Error bars are SQRT(N) type, based on total counts in the measuring apertures prior to background subtraction. The energy band is 2 to 6 keV.
The detailed results of these models will be given in Harris et al. (2003), but here we summarize the results by noting that for the large source size of 0.3″, values of the half-life, $\tau_1$, for the highest energy electrons are greater than a year for all values of $\delta < 16$. Since large $\delta$’s require very small angles of the jet axis to the line of sight (l.o.s.), the data support the smaller diameter alternatives.

For models with the source size given by the light travel time, small values of $\delta$ have values of $\tau_1$ too small to match our data and large values of $\delta$ predict $\tau_1$ significantly larger than a year. The parameters that best fit the data are provided by $\delta = 4$. For this model, the characteristic angle to the l.o.s. is 14°, consistent with canonical values from radio considerations; a magnetic field strength of 1 mG; and a total energy requirement (field plus particles) of $10^{48}$ ergs. In the jet frame, the time required to double the intensity (and thus double the total energy reservoir) is $\approx 4 \times 10^7$ s, which translates into a very modest ‘drain’ on jet power of $<10^{41}$ erg s$^{-1}$. The photon energy density in the jet frame is dominated by the synchrotron spectrum, but is of order 5% of the magnetic field energy density.

Since synchrotron self-Compton models under predict the observed X-ray emission by a large factor and IC/CMB models require unreasonable values of $\Gamma$ and angles to the l.o.s. (Harris & Krawczynski, 2002), the “modest beaming” synchrotron model appears to be the model of choice.

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