FLARING X-RAY EMISSION FROM HST-1, A KNOT IN THE M87 JET

D. E. Harris, J. A. Biretta, W. Junor, E. S. Perlman, W. B. Sparks, and A. S. Wilson

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ABSTRACT

We present Chandra X-ray monitoring of the M87 jet in 2002, which shows that the intensity of HST-1, an optical knot 0.8′ from the core, increased by a factor of 2 in 116 days and a factor of 4 in 2 yr. There was also a significant flux decrease over 2 months, with suggestive evidence for a softening of the spectrum. From this variability behavior, we argue that the bulk of the X-ray emission of HST-1 comes from synchrotron emission. None of the other conceivable emission processes can match the range of observed characteristics. By estimating synchrotron model parameters for various bulk relativistic velocities, we demonstrate that a model with a Doppler factor δ in the range 2–5 fits our preliminary estimates of light-travel time and synchrotron loss timescales.

Subject headings: galaxies: active — galaxies: individual (M87) — galaxies: jets — magnetic fields — radiation mechanisms: nonthermal

On-line material: color figure

1. INTRODUCTION

With the advent of Chandra X-ray observations of radio jets, evidence supporting the synchrotron process for the origin of the X-ray emission from the jets of low-luminosity radio galaxies has grown. One line of evidence is the similarity of the X-ray morphology to the radio and optical structures, which are most likely synchrotron emission because of the detection of linear polarization. Another argument is that the values of the spectral index of power-law fits to the X-ray spectra are generally steeper than the radio spectra whereas inverse Compton (IC) models predict αc ≤ α, (e.g., Hardcastle et al. 2002; Harris & Krawczynski 2002).7

In this Letter we exploit another fundamental difference between IC and synchrotron emission: the variability timescale. Although the injection of new relativistic electrons can produce the same rise time for both processes, the characteristic loss timescales are vastly different. All IC models require relatively low energy relativistic electrons. For synchrotron self-Compton (SSC) models, Lorentz energy factors, γ, are normally comparable to the values of a few thousand that are responsible for the observed radio emission. For IC scattering between the relativistic electrons and photons of the cosmic microwave background (IC/CMB), γ ≤ 1000 (Harris & Krawczynski 2002). Synchrotron models, however, require γ ≳ 10 7 with corresponding half-lives of order a year for the sorts of magnetic field strengths commonly estimated for features in radio jets.

Our data show strong intensity variability from the unresolved core and HST-1. We use the flux doubling time to derive an upper limit to the source size and the decay time to constrain the timescale for E2 losses and, in turn, δ. We take the distance to M87 to be 16 Mpc so that t′ = 77 pc.

2. THE X-RAY MONITORING OBSERVATIONS

In 2002 we obtained five observations of 5 ks each on January 16, February 12, March 30, June 8, and July 24. To minimize pileup, we used a readout time of 0.4 s for the standard 1/8th subarray on the ACIS-S3 chip (POG 2001). Data reduction followed the “threads” (CIAO 2.2).9 To recover the inherent resolution of Chandra, we removed pixel randomization and rebinned the data to 0.1 native ACIS pixels. For three energy bands (soft, S = 0.2–0.75 keV, medium, M = 0.75–2 keV, and hard, H = 2–6 keV) flux maps were obtained by standard procedures; a correction was applied for degradation of the quantum efficiency by measurement of fixed regions of hot gas emission near the jet. A wide-band image was made by adding the three energy bands, and Figure 1 shows the result of averaging our flux maps.

Our monitoring shows striking variability in both HST-1 and the unresolved core (which could well come from jet segments closer than 0.4′ from the nucleus). The other knots show weak or no variability and will be analyzed in a future paper. Contour diagrams of the core and HST-1 for each observation can be found in Harris (2003a); here we show light curves for the core and HST-1 (Fig. 2). The photometry was obtained by taking small circles with radii 0.04′ and subtracting the background from rectangles above and below the jet (with a total area of 13.6 arcsec2).

The largest increase occurs for HST-1 between the March and July observations with over a factor of 2 brightening in 116 days.10 This implies that the emitting volume of the variable component has a characteristic size less than or equal to the light-travel time,11 which is 0.1 pc for a stationary source. The brightening in the core between our last two observations showed a similar rate of increase with a 20% gain in 46 days.

The relative increases in the three energy bands demonstrate a hardening of the spectrum for HST-1 between 2002 March and July (compare the rates of increase in each band in Fig. 2). The intensity increase was a factor of 2.7 ± 0.3 for the hard,

8 See http://cxc.harvard.edu/proposer/POG/index.html.
9 See http://cxc.harvard.edu/ciao/threads.
10 A brightening was also seen in our HST monitoring between 2001 July and 2002 July. Those data will be analyzed in a separate paper (J. A. Biretta et al. 2003, in preparation).
11 However, see Protheroe (2002) for caveats.
Fig. 1.—*Chandra* X-ray image of the M87 jet constructed by averaging the data of Wilson & Yang (2002) taken in 2000 July, together with our five observations. The contours increase by factors of 2 in brightness, with the lowest contour level being $1 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$ pixel$^{-1}$ in the 0.2–6 keV band. Jet features are labeled according to the standard convention, and a 10′′ scale bar is shown. ACIS pixel randomization has been removed, the data were regridded to a pixel size of 0.049′′, and a Gaussian smoothing function of FWHM $= 0.25$ was applied. [See the electronic edition of the Journal for a color version of this figure.]

1.7 ± 0.1 for the medium, and 1.6 ± 0.1 for the soft band. Although we defer spectral analysis to a later paper, this hardening produced a change in the X-ray spectral index from $\alpha_x \approx 1.35 \pm 0.1$ (prior to 2002 May) to $\alpha_x = 1.05 \pm 0.07$ (for 2002 July).

The "cleanest" drop occurs for HST-1 between the 2002 January and February observations. The intensity ratios (February over January) for these 27 days are $0.79 \pm 0.09$ ($H$), $0.83 \pm 0.04$ ($M$), and $0.87 \pm 0.05$ ($S$). While these values are the same within the errors, there is a progression consistent with expectations for $E^2$ losses (but contrary to that of increased absorption): the hard band is dropping faster than the soft band. A similar effect is seen in the core decay between March and June: the hard band dropped $32\% \pm 7\%$, while the medium band dropped $14\% \pm 5\%$.

All of these timescales are subject to considerable error. Although the statistical errors for the flux values are less than 10%, there will always be some flux present that is not part...
of the variable component, and our sampling interval is not small enough to determine shorter variations.

Variability of a synchrotron source can result from a number of effects such as changes in any of the absorption along the line of sight, the magnetic field strength $B$, the number of particles contributing to the radiation in a given band, or the beaming factor (Protheroe 2002).

Adiabatic compression or expansion is particularly effective in changing the radiated power since the electrons gain or lose energy and, at the same time, $B$ changes to augment the effect. Given a power-law electron energy distribution $N(E) \propto E^{-\gamma}$, there should be no change in $p$. On the other hand, if the effects of a high-energy cutoff extend down to the energy range of interest, a compression would cause an increase of intensity accompanied by a spectral hardening since the emission from a fixed observing band would come from lower energy electrons and the spectral curvature would be shifted to higher energies. However, for the remainder of this Letter we focus on an alternative synchrotron model based on changes to the number of radiating particles.

For this model, increased intensity arises from the injection of new radiating particles with a spectrum flatter than the one that existed previously. The spectral softening that accompanies flux decline comes from normal $E^2$ losses. The chief difference in these models is that the compression/expansion model requires $N(E)$ depart from a power law. Our data allow spectral curvature, but the statistics are not good enough to demand curvature.

3. THE SPECTRAL ENERGY DISTRIBUTION OF HST-1

In order to derive synchrotron model parameters, we need to know the overall spectral distribution of the emitted energy. Both the radio and optical morphologies of the inner jet are shown in Figure 3 of Perlman et al. (1999) with 0′.2 resolution. At higher resolution (Fig. 1 of Biretta, Zhou, & Owen 1995) it can be seen that there are a series of several knots between 0′.8 and 1′.2 from the core. $HST$ data demonstrate that the brightest upstream knot is slowly moving but the downstream knots are moving with an apparent speed of $\sim 6c$ (Biretta, Sparks, & Macchetto 1999). Our feature “HST-1” (Fig. 1) corresponds to the upstream, optically brighter part of this segment of the jet. We take the radio flux density corresponding to the X-ray knot to be 3.8 mJy, as measured on the high-resolution 15 GHz map. From a new VLA observation, we derive an upper limit of 2 mJy at 43 GHz.

The optical flux densities come from the detailed spectral analysis of Perlman et al. (2001). The spectrum is shown in Figure 3, and for the purposes of § 4, we approximate these data with a single power law between $10^9$ and $10^{18}$ Hz with $\alpha = 0.68$ and amplitude determined by $S(2$ keV $) = 100$ nJy, parameters that describe the observables to within a factor of 2.

4. A “MODEST BEAMING” SYNCHROTRON MODEL FOR HST-1

Previous analyses have demonstrated that the X-ray jet emission of M87 is not thermal emission (Wilson & Yang 2002; Marshall et al. 2002; Biretta, Stern, & Harris 1991), is not SSC emission (ibid), and is not IC/CMB emission because of the large values of $\Gamma$ and small angles to the line of sight required (Harris & Krawczynski 2002). The X-ray spectra of the knots are much steeper than in the radio or optical and strongly favor synchrotron radiation (Wilson & Yang 2002), confirming the conclusion of Biretta et al. (1991). Our variability data are fully consistent with X-ray synchrotron emission, and it remains only to demonstrate that plausible physical parameters can be found with a simple model that posits that the jet has a relativistic bulk velocity, as implied by the one-sided emission at all frequencies. In this section, we do that for HST-1.

Using the time required for the flux to double provides an upper limit to the source size. To use the observed decline, we take the observed variables back to the jet frame, calculate the properties of the synchrotron source assuming equipartition conditions (Pacholczyk 1970), and then evaluate the half-life of the electrons responsible for the X-ray emission, both in the jet frame and as observed at Earth. We also compare energy densities in the magnetic field and in the synchrotron photons. We performed these calculations for eight values of $\delta$ between 1 and 16. For converting various quantities to the jet frame and back, we used expressions from the Appendix of Harris & Krawczynski (2002). The results for representative values of $\delta$ are shown in Table 1.

We have made model-specific estimates of how to relate an observed decline of 21% (in the hard band in 27 days) to the effects of $E^2$ losses on the electron distribution (Harris 2003b). We find consistency for $\delta$ in the range 2–5. However, the main conclusion is that regardless of the precise model and the actual values found for the rate of decline, the observed timescales for decay are fully consistent with the beaming parameters for a jet angle of order $10^\circ$–$17^\circ$ (to the line of sight) suggested by the $HST$ proper-motion studies of Biretta et al. (1999) in their Table 3. Larger beaming factors imply weaker fields and longer half-lives, and vice versa. A recent $HST$ observation shows the varying region to be unresolved in the optical/UV, independently placing an upper limit of 0′.02 (1.5 pc) on its size (cf. the radii in Table 1).

Values of $\delta$ in the range 2–5 involve very modest synchrotron luminosities in the jet frame, equipartition magnetic field strengths of order 1 mG, and a total energy stored in particles and fields that can be supplied by a low drain on the jet kinetic energy.
energy, \(\sim 10^{46} \text{ ergs s}^{-1}\), a value \(\lesssim 1\%\) of the jet power estimated by Young, Wilson, & Mundell (2002). With these parameters, the effective energy density of the CMB as seen by the jet is less than the synchrotron energy density for most choices of allowed \(\Gamma\), and the combined photon energy density \(\lesssim 0.2\%\) of that in the magnetic field for all \(\delta > 2\). Thus, the bulk of the energy loss is via the synchrotron, not the IC channel. The model predicts that the optical emission will decay with a timescale of order 10 times longer than that we observe for the X-rays since \(\tau_{1/2} \approx 1/\gamma\). For a straight jet, an angle to the line of sight of \(\theta = 10^\circ\) implies a total jet length of just under 10 kpc.

These estimates are based on decay timescales, and our results would change if the actual decay time is shorter than our current estimate, in which case we would choose a smaller value of \(\delta\). If the magnetic field is substantially less than the equipartition value (and thus \(\tau_{1/2}\) would be larger than calculated because of the weaker field), we would again choose a smaller \(\delta\). If the source size were to be substantially less than the light-travel time, the field would be larger than calculated, half-lives would be shorter, and we would select a larger \(\delta\).

### 5. CONCLUSIONS

We find that a synchrotron model with a beaming factor of \(\delta = 2–5\) gives a good fit to our observations for HST-1 and is compatible with radio and optical interpretations. It remains to be seen if similar models can be constructed for powerful jets such as that in 3C 273. Many of the gross features, such as the progressions of X-ray emission being stronger close to the core, whereas the radio intensity increases moving out along the jet, as well as the slight shifts in brightness (radio brighter downstream of the X-ray peak for some knots), are the same in M87 and 3C 273. It is also worth noting that if M87 were farther away or observed with poor resolution, the variability that we now know arises from a knot in the jet might well be ascribed to conditions very close to the black hole (as in blazar variability studies). We shall continue to monitor the jet of M87 with Chandra between 2002 November and 2003 July with eight observations, and the jet will also be monitored at similar intervals with HST. These data should provide refined estimates of variability timescales, spectral evolution for the core and HST-1, and variability in the other knots.

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### REFERENCES

Biretta, J. A., Sparks, W. B., & Macchetto, F. 1999, ApJ, 520, 621
Biretta, J. A., Stern, C. P., & Harris, D. E. 1991, AJ, 101, 1632
Biretta, J. A., Zhou, F., & Owen, F. N. 1995, ApJ, 447, 582
Hardcastle, M. J., Worrall, D. M., Birkinshaw, M., Laing, R. A., & Bridle, A. H. 2002, MNRAS, 334, 182
Harris, D. E. 2003a, NewA Rev., in press (astro-ph/0302290)
———. 2003b, in Radio Astronomy at the Fringe: A Workshop on Solar Polarization, ed. J. A. Zensus, M. H. Cohen, & E. Ros (San Francisco: ASP), in press (astro-ph/0302097)
Harris, D. E., & Krawczynski, H. 2002, ApJ, 565, 244
Marshall, H. L., Miller, B. P., Davis, D. S., Perlman, E. S., Wise, M., Canizares, C. R., & Harris, D. E. 2002, ApJ, 564, 683
Pacholczyk, A. G. 1970, Radio Astrophysics (San Francisco: Freeman)
Perlman, E. S., Biretta, J. A., Sparks, W. B., Macchetto, F. D., & Leahy, J. P. 2001, ApJ, 551, 206
Perlman, E. S., Biretta, J. A., Zhou, F., Sparks, W. B., & Macchetto, F. D. 1999, ApJ, 517, 2185
POG 2001, Chandra Proposers’ Observatory Guide, TD 403.00.004 (Cambridge: CXC)
Protheroe, R. J. 2002, Publ. Astron. Soc. Australia, 19, 486
Wilson, A. S., & Yang, Y. 2002, ApJ, 568, 133
Young, A. J., Wilson, A. S., & Mundell, C. G. 2002, ApJ, 579, 560