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A FLARE IN THE JET OF PICTOR A

H. L. Marshall[1], M. J. Hardcastle[2], M. Birkinshaw[3,4], J. Croston[5], D. Evans[1], H. Landt[6], E. Lenc[7], F. Massaro[3],
E. S. Perlman[8], D. A. Schwartz[3], A. Siemiginowska[3], Ł. Stawarz[9,10], C. M. Urry[11], and D. M. Worrall[3,4]

[1] Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA;
hermanm@space.mit.edu, devans@space.mit.edu
[2] School of Physics, Astronomy, and Mathematics, University of Hertfordshire, College Lane, Hatfield, Hertfordshire AL10 9AB, UK; m.j.hardcastle@herts.ac.uk
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; Mark.Birkinshaw@bristol.ac.uk, fmassaro@head.cfa.harvard.edu,
das@head-cfa.harvard.edu, aneta@head.cfa.harvard.edu, D.Worrall@bristol.ac.uk
[4] Department of Physics, University of Bristol, Tyndall Ave., Bristol BS8 1TL, UK
[5] School of Physics and Astronomy, University of Southampton, University Road, Southampton SO17 1BJ, UK; J.Croston@soton.ac.uk
[6] School of Physics, University of Melbourne, Parkville, VIC 3010, Australia; hlandt@unimelb.edu.au
[7] CSIRO Australia Telescope National Facility, P.O. Box 76, Epping, NSW 2121, Australia; Emil.Lenc@csiro.au
[8] Department of Physics and Space Sciences, Florida Institute of Technology, 150 W. University Blvd., Melbourne, FL 32901, USA; eperlman@fit.edu
[9] JAXA/ISAS, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan; stawarz@slac.stanford.edu
[10] Astronomical Observatory, Jagiellonian University, ul. Orla 171, Kraków 30-244, Poland
[11] Department of Physics, Yale University, New Haven, CT 06511, USA; meg.urry@yale.edu

ABSTRACT

A *Chandra* X-ray imaging observation of the jet in Pictor A showed a feature that appears to be a flare that faded between 2000 and 2002. The feature was not detected in a follow-up observation in 2009. The jet itself is over 150 kpc long and about 1 kpc wide, so finding year-long variability is surprising. Assuming a synchrotron origin of the observed high-energy photons and a minimum energy condition for the outflow, the synchrotron loss time of the X-ray emitting electrons is of order 1200 years, which is much longer than the observed variability timescale. This leads to the possibility that the variable X-ray emission arises from a very small sub-volume of the jet, characterized by a magnetic field that is substantially larger than the average over the jet.

Key words: galaxies: active – galaxies: individual (Pictor A) – galaxies: jets – X-rays: galaxies

1. INTRODUCTION

Surveys using the *Chandra X-ray Observatory* have been very successful at detecting knots in quasar jets (e.g., Marshall et al. 2005; Sambruna et al. 2004). Two mechanisms are generally cited when explaining the origin of the X-rays: synchrotron emission from high-energy electrons and inverse Compton scattering of cosmic microwave background photons by low-energy electrons in knots in relativistic bulk motion along the line of sight (see Harris & Krawczynski 2006; Worrall 2009, for reviews). In the synchrotron case, variability might be expected on a timescale of years due to the short loss times for electrons of sufficient energy to produce X-rays. In the inverse Compton model, however, variability timescales could be much larger, with rise times longer than the knot light crossing time and decay times dictated by radiative lifetimes larger than 10^4 yr. In both cases, adiabatic loss timescales should be of order the light crossing time.

Variability studies have generally been limited to nearby objects such as Cen A (Goodger et al. 2010) and M 87 (Harris et al. 2009). In the case of M 87, the *HST*-1 knot was found to flare by a factor of 50 over a period of five years, becoming much brighter than the nucleus. While the M 87 jet is about 7 pc across, the upstream end of the *HST*-1 knot is only 1.9 pc across, so a secular increase over five years is reasonable. However, the increase is not smooth and there is a factor of 2 drop in less than half a year, so the variation could be up to a factor of 10 faster than the light travel time across the emission region. Harris et al. (2003) explain this by Doppler boosting by a factor of $\delta \approx 5$. Both Cen A and M 87 are FR I radio galaxies, which are more common—and thus more nearby—than FR II radio galaxies and quasars with higher power jets. Knots in high-power jets are larger but less well resolved, and variability has not been

reported. For example, one attempt to find variability in the X-ray emission from a jet in a quasar, 3C 273, yielded a null result (Jester et al. 2006).

Pictor A is an FR II radio galaxy at a redshift of 0.035. For $H_0 = 70.5$ km s^{-1} Mpc^{-1}, $1''$ corresponds to about 700 pc. Its pencil-like X-ray jet was found in *Chandra* observations by Wilson et al. (2001, hereafter WYS01), extending $1.'9$ from the core, oriented toward the partially resolved western hot spot $4.'2$ from the core. They estimated that the jet's typical width was about $2.''0$ or 1.4 kpc. Based on the assumption that the jet X-ray emission was produced by the inverse Compton process, and using the radio galaxy arm-length asymmetry to infer an angle to the line of sight, they suggested that a plausible scenario was that the magnetic field in the jet was 2 μG, about a factor of 6 below the equipartition value, and that the Doppler factor in the jet was ~2.6. However, subsequent tighter constraints on the X-ray photon index (Hardcastle & Croston 2005) mean that the jet would be required to have a significantly steeper low-energy electron energy index than the lobes for an inverse Compton model to be viable. Hardcastle & Croston (2005) argue that this is implausible and that the X-ray emission of the jet must be dominated by the synchrotron process; if so, the X-ray emission gives us no direct information on the Doppler factor or jet speed, other than ruling out highly beamed and/or sub-equipartition models. While the WYS01 estimate of the angle to the line of sight remains plausible, there are very large uncertainties associated with the use of the arm-length asymmetry to estimate θ. As Pictor A is a broad-line radio galaxy, low-luminosity unified models imply $\theta \lesssim 45°$; the fact that the source is observed as a lobe-dominated object and the projected linear size of the source probably requires $\theta \gtrsim 10°$.

Examining the archival *Chandra* data through 2002 (observation IDs 345, 3090, and 4369), we found evidence for flares in
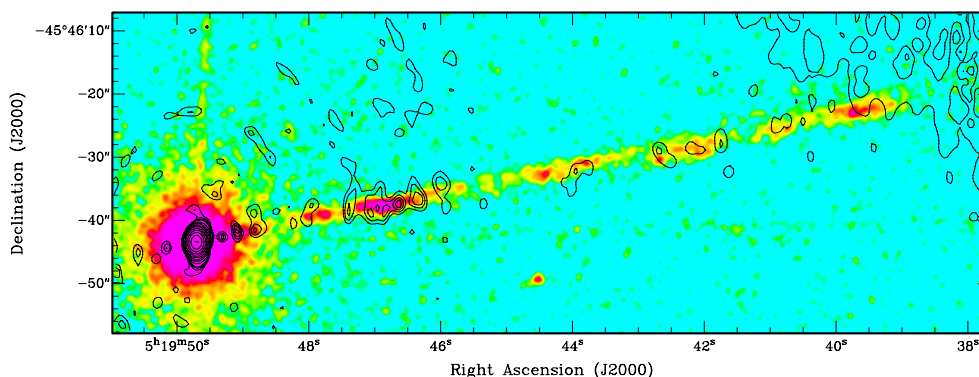
Figure 1. X-ray image of the Pictor A jet from all data listed in Table 1, superposed with radio flux density contours from a new map at 4.8 GHz taken with the ATCA. There are clear associations of radio emission with features in the X-ray emission.

Table 1
Chandra Observations of Pictor A

Chandra Obs ID	Off-axis Angle (′)	Live Time (s)	Date
346	0.7	25733	2000-Jan-18
443	6.4	5058	2000-Jun-28
3090	4.1	46362	2002-Sep-17
4369	4.1	49123	2002-Sep-22
11586	0.8	14257	2009-Dec-12
12039	0.8	23737	2009-Dec-07
12040	0.8	17319	2009-Dec-09

the jet at 3σ significance. The observations were not homogeneous, with one taken $1'$ from the core and the other centered at the hot spot about $4'$ away, so the point-spread function (PSF) at the core was degraded. So, to improve the variability test and to check for new flares, we obtained new images. Here, we report on the previous evidence for variability and the results from the new observations. A detailed analysis of the jet will be the subject of a later paper.

2. OBSERVATIONS AND DATA REDUCTION

Pictor A was observed in 2000, 2002, and 2009 by the *Chandra X-ray Observatory* (see Table 1). For observation 443, the core was over $6'$ off-axis, so the core's PSF is highly extended by comparison to the other observations. Due to the broadened PSF and the modest exposure, this observation was not used in the analysis. Offsets of less than $1'$ do not degrade the PSF, while at $4'.1$ off-axis, the PSF is a factor of 2.7 wider than on-axis, based on figures in the *Chandra* Proposers' Observatory Guide. Unless mentioned otherwise, we selected events from the files processed using `ciao` in the energy range 0.5–7.0 keV. A new radio map was obtained using the Australian Telescope Compact Array (ATCA). The map, shown in Figure 1, shows structure in the inner jet that was not previously observed, which follows features observed in the X-ray image. The radio map will be discussed in more detail in a separate paper.

Upon examining the data from 2000 and 2002, we found possible flares in the jet, as shown in Figure 2. The most significant feature was at about $48''$ from the core in the 2000 image. A preliminary analysis found 18 counts in obsID 346 from 2000 in a $3'' \times 3''$ region centered on the feature while the combination of the two observations from 2002 yielded only 15 counts in a longer exposure. A binomial probability test that there would be $\geqslant 18$ of the 33 counts in the first observation

when 7.6 counts were expected (under the null hypothesis of no variability) gave a probability of significance of 9×10^{-4} or an equivalent Gaussian significance of 3.7σ. Accounting for the number of bins examined along the jet reduced the significance to 2.6σ. The flare events were not found to be clustered in time, so ACIS flares were ruled out. Similarly, the energy distribution of the events in the flare was consistent with that of the rest of the jet and significantly different from that of the background. So, the events are consistent with that originating in the jet.

The 2009 observations were then combined with the 2002 data for a more stringent test of the flare at $48''$ from the core. We chose a bin size of $1''$ along the jet to make it straightforward to find a point source within a lumpy structure (i.e., the jet in its nonvarying "normal" state). A running sum of three bins was used to find significant deviations. In the cross-jet direction, the events were taken from a region within $\pm 2''$ of the centerline set to a position angle of $-78^\circ.8$ (where positive is E of N). These values were determined by taking profiles of the jet at various positions along it and ensuring that a selection this wide would collect over 90% of the counts. The jet "wiggles" slightly and broadens along its length from unresolved to about $2''$ across, so the selection region was wider than the PSF across the jet.

We compared the profile from the 2000 observation against a model consisting of two components: a background-subtracted net model profile and an empirically derived background specific to the 2000 observation. The net model profile was constructed from the 2002 and 2009 observations (see Figure 3). Backgrounds were determined for each data subset by taking $\pm 2''$ swaths at six position angles avoiding chip gaps and other detector features. The background profiles were subtracted from the count profiles to form the net model, which was then scaled for comparison to the 2000 profile. Because the ACIS filter is accumulating a contaminant, the event energy distribution in 2009 is deficient below 1 keV, making it inappropriate to normalize those data by a simple factor relating to exposure. Fortunately, the event energy distributions of the inner and outer halves of the $2'$ long jet are indistinguishable, indicating that the X-ray spectrum does not vary significantly along the jet. So, we chose to normalize the model to match the total counts in the 2000 profile between $10''$ and $120''$ from the core (after accounting for background), a factor of 0.213. The background uncertainties end up being negligible, but the background itself is important, contributing as much as the net model does in many locations.

The result is shown in Figure 3. The most significant deviation between the 2000 data and the combination of the other data sets is centered at $48''$ from the core. The Poisson probability of the deviation was 8.0×10^{-6} or an equivalent Gaussian significance
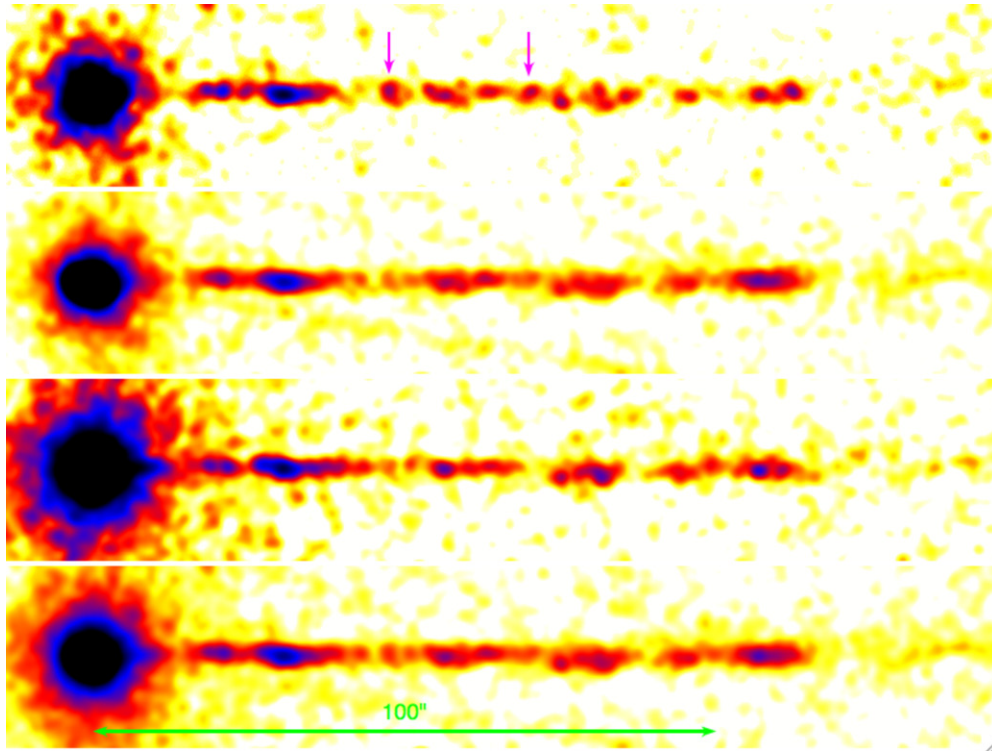
Figure 2. X-ray images of the Pictor A jet at several epochs: 2000 (top), 2002 (second from top), 2009 (second from bottom), and the total (bottom). All are rotated by $11°2$ to orient the jet to the right. The images were smoothed by a two-dimensional Gaussian with a σ of $0''8$. The 2002 image has a readout streak at about $10°$ to the jet. Possible knot flares are indicated with magenta arrows.

of 4.3σ. A similar test between the 2009 and 2002 data yielded no features more significant than 3.2σ; so combining these two epochs is justified a posteriori and the result provides some confidence that the analysis method does not overproduce false positive signals. Accounting for the number of independent trials reduces the significance to about 3.4σ. The feature is robust, showing up at 3.4σ when testing a running sum of three $0''5$ bins; at this binning, a feature at $70''$ is significant at 3.3σ (before accounting for the number of trials). There are only 13.9 net counts in the test region, so the count rate in the $48''$ feature is not well determined: 0.00054 ± 0.00019 counts s^{-1}. For a power-law spectrum with $\Gamma = 1.94$ and a Galactic column density of 5.8×10^{20} cm^{-2}, as found by WYS01 for the entire jet, the flux of the flare is 3.5×10^{-15} erg cm^{-2} s^{-1} in the 0.5–7.0 keV band. This flux corresponds to about 2×10^{-15} erg cm^{-2} s^{-1} in the 0.5–2.0 keV band, above which there are about 600 X-ray sources per square degree (Tozzi et al. 2001). In the $4''$ wide area of the jet that was searched for flares from $10''$ to $120''$ from the core, we expect less than 0.02 unrelated X-ray sources; so the hypothesis that the flare comes from a background source can be ruled out at the 98% confidence level.

It is important to determine if the flare is consistent with a point source. The jet is resolved in the cross-jet direction just downstream from the $48''$ flare location. Combining all data sets, the cross-jet profile between $50''$ and $65''$ from the core fits a Gaussian with $\sigma = 0''87 \pm 0''05$. An unresolved jet should have a one-dimensional profile comparable to that of the ACIS readout streak from the unresolved core, whose profile is a Gaussian with $\sigma_{\mathrm{psf}} = 0''382 \pm 0''015$. Assuming that the true jet profile also matches a Gaussian, then $\sigma_j = (\sigma^2 - \sigma_{\mathrm{psf}}^2)^{1/2}$, giving the jet FWHM $= 2.35\sigma_j = 1''83 \pm 0''18$. A proper spatial test would check for a variable point-like feature embedded in an extended background jet. For a simple check, we examined
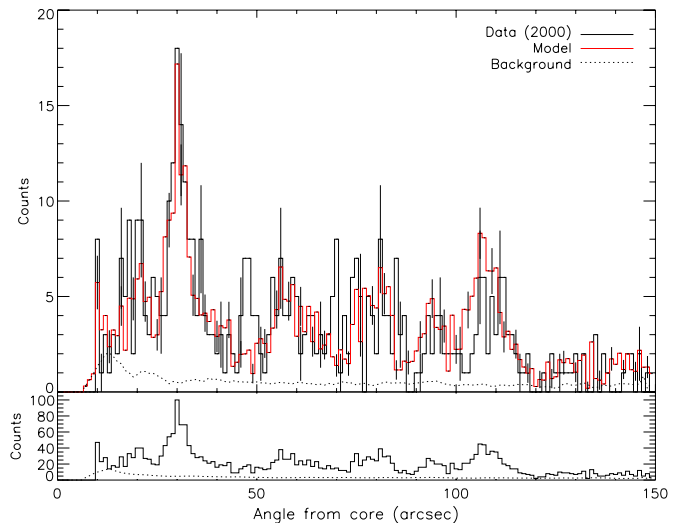

Figure 3. Top: count profile of the X-ray emission along the jet for the 2000 observation compared to a model based on the remaining observations. Both the data and the model include smoothed background, shown separately. The feature at $48''$ from the core is a possible flare in the jet that was not apparent in the 2002 observation. Another possible feature is at $70''$ from the core. Bottom: count profile for all observations combined, for reference. Note that the jet is weak but clearly detected beyond $120''$ from the core.

the 2000 event list in detail. We counted the events in concentric $1''$ and $2''$ diameter circles, which should contain 50% and 90% of the power. With 13.9 net counts in the $3'' \times 4''$ sample region, we expect 12.5 counts from the putative point source within the larger circle and 7 within the smaller one. We found a location within the sample region where there are 10 counts within the larger circle and 4 within the smaller circle, which is reasonably

consistent with the expectation, considering the small number of counts. Thus, we conclude that there could have been a single unresolved knot within the jet that caused the observed flare.

3. DISCUSSION

Using the formalism of Worrall ([2009]), we estimate the average equipartition magnetic field in the jet to be $B_{eq} = 17\,\mu G$, similar to the value obtained by WYS01 in the absence of beaming. Further below we assume that the Pic A jet is indeed close to the minimum energy condition, as justified by observations of terminal hot spots and lobes in powerful radio sources (e.g., Kataoka & Stawarz [2005]). We measured the jet flux density to be 128 mJy at 1.4 GHz and assume $\gamma_{min} = 100$, an electron energy index of 2 breaking to 3 before the X-ray band and that the radius of the jet is about $1''$, as estimated by WYS01. For these assumptions, Lorentz factors of the electrons that produce 1 keV X-rays are $\gamma \approx 7 \times 10^7$. The corresponding synchrotron loss time, $\tau \approx 1200$ yr, is similar to the dynamical time scale $t_{dyn} = \ell/c = 2000$ yr, setting the knot size to the FWHM of an unresolved source ($0''9$), but both are much larger than the variability timescale of 2 years.

Doppler beaming would reduce the estimated intrinsic value of B_{eq} by a factor of $\delta = 1/[\Gamma(1 - \beta\mu)]$, where βc is the speed of the jet moving at angle $\theta = \cos^{-1}\mu$ to the line of sight and $\Gamma = (1 - \beta^2)^{-1/2}$. As δ increases, the efficiency of inverse Compton scattering of microwave background photons increases rapidly, affecting the observed X-ray flux. In particular, WYS01 estimated that $\delta \approx 7$ would allow all the observed X-rays to be produced by the inverse Compton process with $B = B_{eq}$, although this should be taken as an upper limit if the jet X-rays are dominated by synchrotron emission as argued by Hardcastle & Croston ([2005]). Increasing the jet beaming would also affect any X-ray emission resulting from the synchrotron process. For a fixed observed photon energy, E (e.g., 1 keV), and the assumed minimum energy condition, the Lorentz factor of the electrons in the jet rest frame $\gamma \propto \sqrt{E/B}$ is the same as that inferred in the observer frame, since the photon energy transforms by the same factor δ as B_{eq} scales. The radiative lifetimes, however, scale as $1/B^2$ and would increase as δ^2 in the rest frame or δ in the observed frame, exacerbating the lifetime discrepancy.

Ignoring beaming for now, setting t_{dyn} to 2 yr leads to an angular size of the emission region of ~ 1 mas. For a knot that radiates a fraction f of the total jet flux from a volume $V \propto \ell^3$, then $B_{eq} \propto (f/\ell^3)^{1/(3+\alpha)}$. Again fixing the observed photon energy, then $\gamma \propto B^{-1/2}$ and $\tau \propto B^{-3/2} \propto \ell^{3\xi}/f^\xi$, where $\xi = \frac{3}{6+2\alpha}$. Setting $\alpha = 0.5$ for our assumed spectral shape gives $\xi = 3/7$. So, if ℓ is 10^3 smaller, then τ is a factor of ~ 7200 smaller. For the $48''$ flare, $f \approx 0.03$, so $\tau \sim 0.7$ yr, which is consistent with the observed flare. The local B field would be ≈ 2 mG, >100 times larger than the average in the jet. Thus, in order to explain flares on a timescale of years within a jet that is about 700 pc in diameter would require (1) X-ray emission from a small knot substantially smaller than the jet cross section and (2) local magnetic fields substantially larger than the average over the jet.

The energy loss timescale of individual relativistic electrons is unlikely to be the factor controlling the rate of fading of a flare since the energy release that is manifest as a flare is also likely to cause expansion of the emitting region. If we take this emitting region to be spherical, with radius R, and the magnetic field within it to be tangled, then the optically thin synchrotron emission from that region scales as $R^{-4\alpha-2}$ because expansion decreases both the magnetic field strength and the energies of the embedded relativistic particles.[12] If the flaring region had $\alpha = 0.5$, then an expansion by 50% would cause it to fade by a factor of 5 and become undetectable against the larger-scale jet emission. Such an expansion is feasible if the flaring region is only 2 ly in diameter.

As very long baseline interferometry (VLBI) observers expand their maps to include knots at $1''$ scales, some knots are showing mas-scale structure. For example, Godfrey et al. ([2009]) found a very compact hot spot 40 kpc from the core of a quasar and Chang et al. ([2010]) detected the *HST*-1 knot in VLBI observations. Examining more cases might well prove to be a fruitful endeavor. Imaging at even $0''1$ scales with the *Hubble Space Telescope* (*HST*) and future generations of X-ray telescopes could well show that jet knots have substantial substructure.

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[12] Different brightness decrease functions arise under different magnetic field configurations or expansion geometries, but most cases show rapid loss of power under adiabatic losses, at sufficiently high observing frequency.