X-Ray Imaging of the Jet From the Supermassive Black Hole M87

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M87 is a giant elliptical galaxy, located 16.4 Mpc away from Earth, and contains one of the largest known super massive black holes with a mass of $M = 6.5 \pm 0.7 \times 10^9$ M⊙ (1). Like many black holes, M87 produces a particle jet (2), which spans a distance just under 10 kpc (3) and is detectable across the electromagnetic spectrum, from radio (4) through optical (5) to X-rays (3) and gamma rays (6). This makes M87 an ideal target to unify the studies of black holes and relativistic jets. M87's jet emission comes from the shocked plasma in so-called "knots" along the spine of the jet. These knots may arise from variations in the energy output of the black hole, for example, as collisions between matter ejected from the vicinity of the event horizon.

Chandra X-ray Observatory observed M87 twice for a total of 26.24 ks as part of the 2017 April Event Horizon Telescope (EHT) campaign. We analyzed these observations to study the X-ray jet. Our RGB image of M87 is shown in Figure 1, with regions marking different parts of the jet. The image was produced by mapping red to low energy photons (0.3-1.25 *keV*), green to medium energy photons (1.25-2.5 *keV*), and blue to high energy photons (2.5-8 *keV*) (Figure 1). We extracted spectra from these regions for further analysis, focusing on the core (i.e., the center), and the nearby knot HST-1 (Figure 2). We fit these spectra with an absorbed power law model (Table 1): interstellar absorption times a power law,

$$\text{Flux} \propto KE^{-\Gamma},$$

where K is a constant, E is energy in keV, and Γ is the slope of the powerlaw, or "photon index." We corrected for a spectral distortion called "pileup" in which at least two photons hit a pixel in a single time frame.

Pileup reduces the apparent brightness and makes the spectrum appear flatter (7). For every model, $\Gamma<2.25$, the previously recorded value (8).

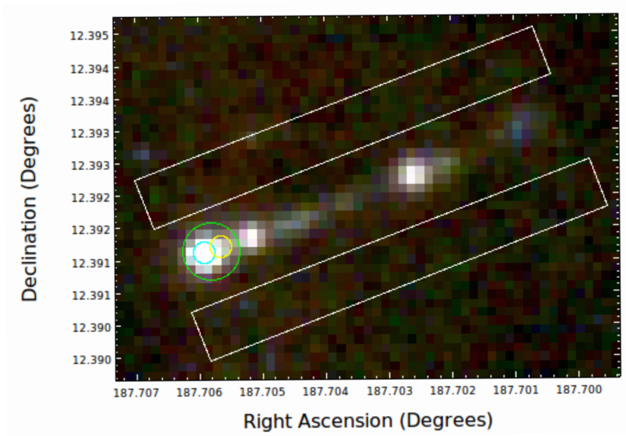

Figure 1. An RGB image of M87, smoothed with a 1 pixel radius gaussian, showing the core and jet knots as well as our extraction regions. The white rectangular regions were used for background subtraction. The smaller yellow circle is the location of HST-1, and the smaller teal circle is the core of M87, where the black hole and galactic center are located. The green circle is the nucleus, which includes both the core and HST-1.

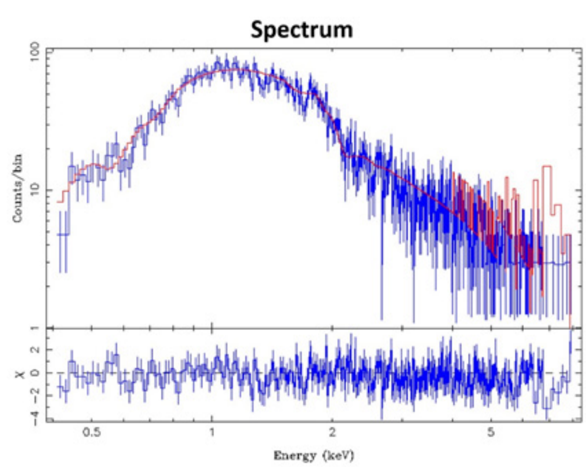

Figure 2. The spectrum of the nucleus in Table 1 (green region in Figure 1). The blue histogram is the observed data and the red line is the best fit function: interstellar absorption times a power law with a "pileup" spectral distortion correction. The fit gave $\chi^2_{red} = 1.05$.

We also created a deconvolved image to remove blurriness caused by the telescope's finite resolution (Figure 3). Our analysis of the deconvolved image suggests that HST-1 was significantly fainter than the core. We found no evidence of strong variability in the X-ray brightness during our observations, but M87 was fainter than in recent observations ($L_X \approx 1.25 \times 10^{41}$ erg s^{-1}). Given HST-1's history of variations and recent trends indicating a fading HST-1 (8), the smaller contribution from HST-1 makes the intrinsic spectrum of the core more readily measurable. In other words, a fainter HST-1 allows for us to measure a more accurate spectrum of the core since there is less light pollution from HST-1 in the core spectrum. There is only a statistically significant amount of absorption in the model when the core is included in the extraction. Interstellar absorption causing turn over in the soft X-ray regime may explain why some of our results differ from previous analysis, but the appearance of this excess absorption in the core is also significant in and of itself. Its origin is currently unknown.

With the finding of a lower Γ and excess N_H, there is significant room for further study of the X-ray spectrum, especially in conjunction with EHT, with context from Chandra's long history of studying M87. An extension of the analysis presented here was included in the publication of the first image of the shadow of a black hole in M87 (10, 11). Future work will involve modeling the radio-γ-ray spectral energy distribution to understand the physics of the jet.

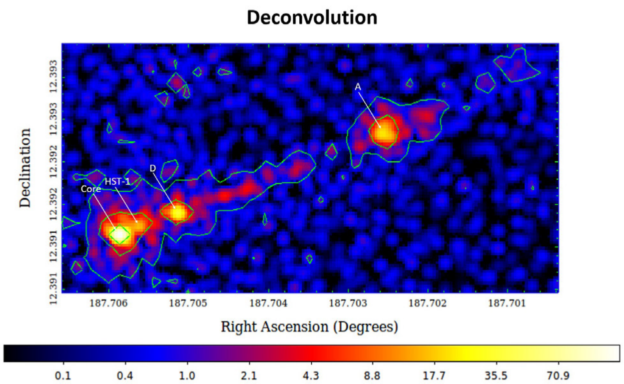

Figure 3. This 0.3-1.5 keV deconvolved image of M87 reveals the relative brightness of HST-1 and the core, plus additional knots in the jet. The image was made using Lucy deconvolution method with 150 iterations following Perlman et. al. (9). This image was smoothed with a 3-pixel radius gaussian and is displayed on a logarithmic intensity scale. The bright spot outside the spine of the jet is not related to super massive black hole or jet.

Table 1. The parameters and models used to model different regions of the inner jet. "Single" refers to one model fitted to both 13.12 ks observations taken on 2017 April 11 and 14. "Separate" refers to two individual models with tied interstellar gas abundance, N_H. "Tied" refers to two individual models with a tied N_H and a tied photon index, Γ.

	Observation	Date (2017 April)	$N_H(10^{20}\mathrm{cm}^{-2})$	Γ	$K(10^{-5}\text{photon keV}^{-1}\,s^{-1})$	χ^2_{red}
Nucleus Single	---	---	5^{+3}_{-3}	$2.05^{+0.06}_{-0.07}$	90^{+5}_{-5}	1.05
Nucleus Separate	20034	11	6^{+3}_{-3}	$1.91^{+0.16}_{-0.08}$	94^{+7}_{-6}	1.00
	20035	14	---	$2.19^{+0.08}_{-0.09}$	86^{+4}_{-6}	---
Nucleus Tied	20034	11	7^{+3}_{-3}	$2.11^{+0.07}_{-0.09}$	98^{+7}_{-6}	1.02
	20035	14	---	---	86^{+5}_{-5}	---
Core Separate	20034	11	9^{+4}_{-4}	$1.8^{+0.2}_{-0.1}$	72^{+7}_{-6}	0.96
	20035	14	---	$2.0^{+0.1}_{-0.2}$	65^{+6}_{-6}	---
Core Tied	20034	11	9^{+4}_{-3}	$1.92^{+0.09}_{-0.09}$	73^{+6}_{-5}	0.96
	20035	14	---	---	64^{+5}_{-5}	---
HST-1 Separate	20034	11	< 2.18	$2.0^{+0.1}_{-0.1}$	13^{+1}_{-1}	0.92
	20035	14	---	$2.0^{+0.1}_{-0.1}$	16^{+1}_{-1}	---
HST-1 Tied	20034	11	< 2.16	$2.0^{+0.1}_{-0.1}$	13^{+1}_{-1}	0.92
	20035	14	---	---	15^{+1}_{-1}	---

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