X-ray Variability in the Core and Jet of M87

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****Due to unforeseen circumstances, I'm unable to be present, but I am available via Slack with any questions or comments!**

We report our spectral variability analysis of the core and jet of M87 based on new and archival *NuSTAR* and *Chandra* observations. *NuSTAR* observations of M87 were collected during Event Horizon Telescope campaigns from 2017-2022 and *Chandra* observations of M87, HST-1, the outer jet, and their Virgo cluster environment were collected between 2000 and 2017. We fit the *NuSTAR* spectra of the core with a broken power law, inferring its variability by keeping the power law spectra of the other (spatially unresolved) jet components fixed. Our modeling suggests that the core spectrum hardens around ~10 keV, and we find increased volatility in the spectrum at higher energies. We find that this broken power-law better fits the data than a simple power-law, suggesting this curvature is intrinsic. Outside a significant brightening in 2018, we also find that across the 3-79 keV range of the data the core has little variability in flux. Continued X-ray observation of the M87 and its core and jet will help to further constrain the properties of its behavior and variability.

Objectives:

1. Determine the shape of the spectrum of M87 by jointly modeling archival X-ray spectra
2. Determine X-ray flux variability over the observing time-scale

Motivation for a Broken Power-law:

1. Power-law fit showed potential curvature in residuals (see red highlighted residuals in Fig 1.)
2. Historical SED models underestimate γ-ray emission, call for a break in the X-ray (see Fig. 2)

Figure 2. Broadband SED Model of M87
(via Event Horizon Telescope Multiwavelength Working Group 2021)[1]

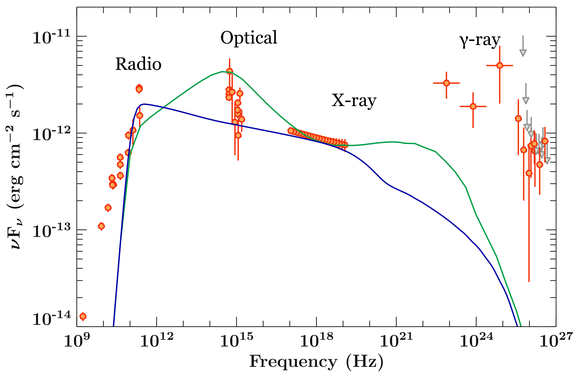


Figure 1. Simple Power-law Model

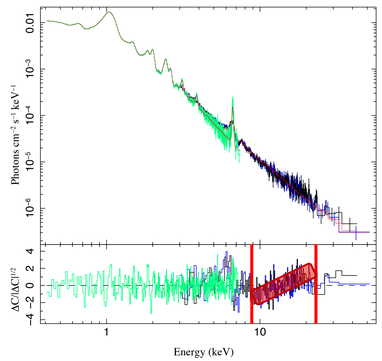
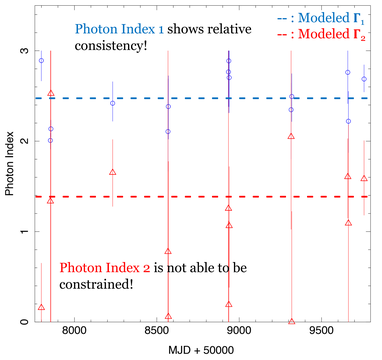


Figure 4. Broken Power-law Photon Index



The Dataset

- 14 *NuSTAR* observations between 04/17 and 06/22
- 3 *Chandra* observations of the surrounding Virgo Cluster (July 2000, July 2002)
- Spatially resolved *Chandra* observations of the core, HST-1, and the outer jet (April 2017)

The Model

Chandra Intracluster Medium

- Absorbed 2-temperature variable abundance emission model

Chandra Spatially Resolved (Core, HST-1, Jet)

- Simple absorbed Power-law for each component, with additional absorber for the core

NuSTAR

- Chandra ICM + Chandra Spatially Resolved + Absorbed Broken Power-law

*Each component had cross-normalization constants applied to account for calibration shifts across instruments

Figure 3. Broken Power-law Model of M87 w/ Power-law Residuals

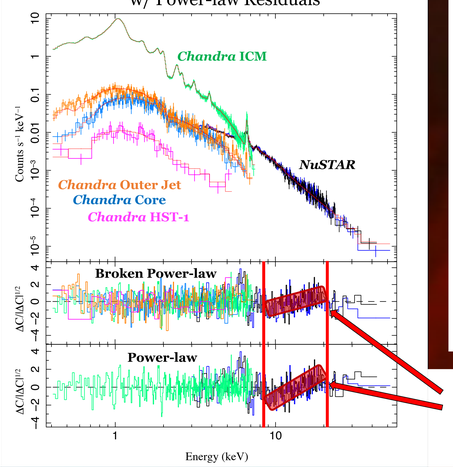
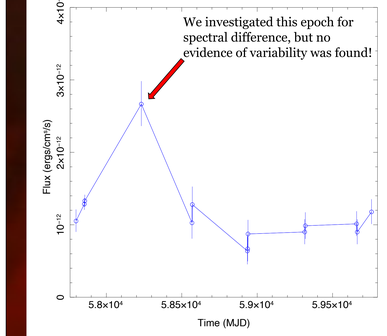


Figure 5. X-ray Light Curve



Shar slope in Power-law residuals suggest possible curvature in spectrum, which flatten out (indicating a better fit) when using a Broken Power-law!

Analysis

- No evidence of spectral variability found (see Fig. 4) across NuSTAR observations, which has 2 implications:
  - The NuSTAR spectra can be stacked to maximize the signal in order to determine the spectral shape
  - When modeling each spectrum individually, the model can be tied across all observations
- Jointly modeled the stacked NuSTAR spectrum with the Chandra spectra (see Fig. 3)
- Jointly modeled each NuSTAR spectrum (with the model tied across observations) and extrapolated the X-ray flux based on the core broken power-law normalization (see Fig. 5)

Results:

1. Broken Power-law Model gave a statistically significant improvement over the Simple Power-law Model
2. Confirm the presence of a spectral break at ~10 keV
3. Light Curve shows little X-ray flux variability, apart from a high-flux state in 2018
4. Broken Power-law currently being incorporated into EHT Multiwavelength Group's ongoing SED Modeling of M87