Investigating Energy Release in Eleven NuSTAR Microflares

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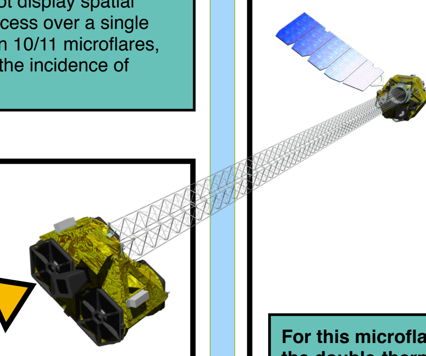
Abstract This work examines eleven solar microflares observed in hard x-rays (HXRs) by the Nuclear Spectroscopic Telescope ARray (NuSTAR). HXR emission in solar flares originates from both hot (millions of Kelvin) plasma and nonthermal accelerated particles, both of which are diagnostic of flare energy release. NuSTAR's direct focusing optics give it a dramatic increase in sensitivity over indirect imagers in the HXR range, allowing for unique insight into the energetics of faint microflares. We discuss the temporal, spatial, and energetic properties of all eleven microflares in context with other published HXR brightenings. They are seen to display several `large-flare' properties, such as impulsive time profiles and earlier peaktimes in higher energy HXRs. For two events where active region background could be removed, microflare emission did not display spatial complexity: differing NuSTAR energy ranges had equivalent emission centroids. Finally, spectral fitting showed a high energy excess over a single thermal model in all events. This excess was found to most likely originate from additional higher-temperature plasma volumes in 10/11 microflares, and from a nonthermal accelerated particle distribution in the last. These spectral results motivate a more general discussion of the incidence of nonthermal emission across these and other similar-magnitude microflares observed by NuSTAR and other HXR instruments.

NuSTAR Solar Microflare Observations

- Two co-aligned focused x-ray telescopes observe from 3-79 keV [1].
- Each optics module has its own focal plane module (FPMA, FPMB)



The NuSTAR Telescope

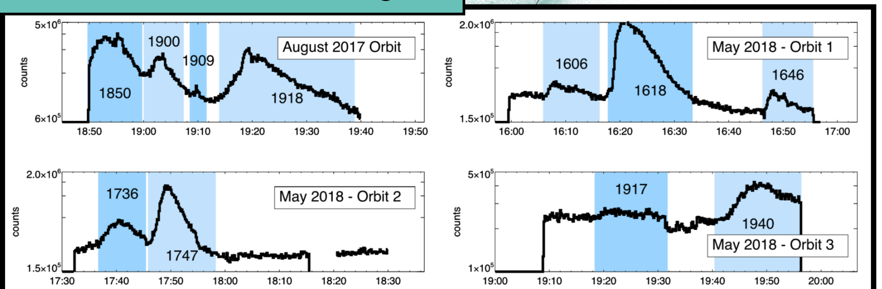
- NuSTAR is **optimized for astrophysical sources**, but also capable of solar observation.
- NuSTAR detector livetime is limited (often <1%) when observing bright solar sources, making it most ideal for observing quiescent solar active regions and **solar microflares.**
- Because of livetime limitations, **the effective NuSTAR energy range for solar observations is more like ~3-15 keV**.

Open Questions about NuSTAR microflares:

- **Is there a 'typical' low-A-class HXR microflare?**
- **Do microflares behave like scaled-down 'standard' flares?**
- **In how many events can we identify non-thermal emission?**

Eleven Microflares from Two Active Regions

Microflare intervals shown in blue:



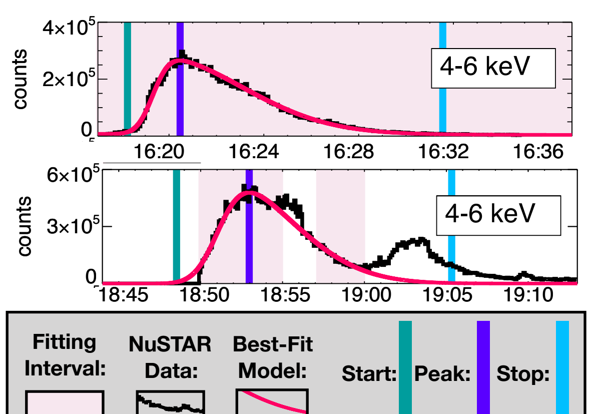
- Livetime-corrected NuSTAR counts (2-10 keV) are shown over four ~1 hour observations of two different regions on two different days.
- Observations were granted due to the 'Great American Eclipse' (August 2017) and the flight of the Hi-C 2.1 sounding rocket (May 2018)
- Flares ranged from GOES sub-A-class to A7.7.

Time Profile Analysis

Automated Start, Peak + End Time Extraction

- Define a model (skewed gaussian + linear background) & fit to NuSTAR lightcurves, then extract characteristic times:
  - **Peak Time: maxima of best-fit model. Start/End Times: 0.1% and 99.9% thresholds for area under skewed gaussian.**

Example Time Profile Fits:



Which 'large flare' temporal properties are seen in these microflares?

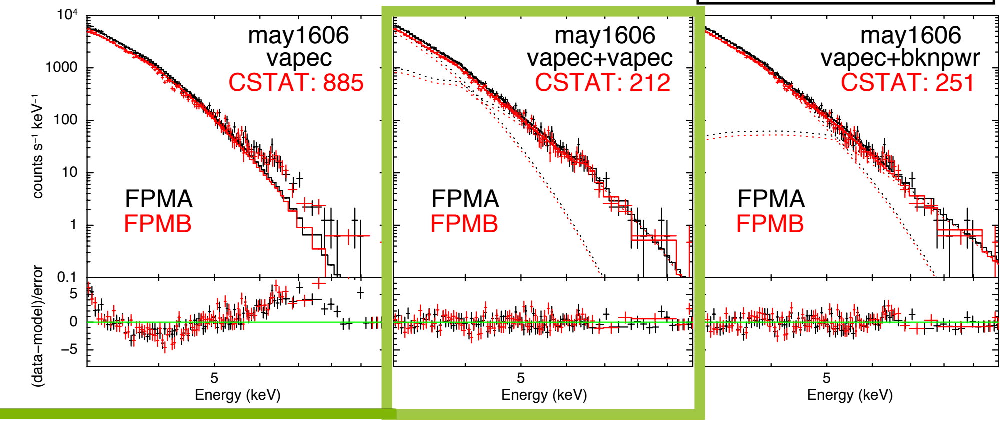
Property	Observed?
Impulsivity in all HXR energies	8/11 events were impulsive in all energy ranges. All were consistent with impulsivity in 2-4, 4-6, 6-8 keV ranges.
Earlier peak times in higher-energy HXR emission	Seen in 10/11 events
Greater impulsivity in higher-energy HXR emission	Inconclusive (due to NuSTAR's limited livetime)

Spectral Analysis - Example Event

Single VAPEC Model
Isothermal Plasma Volume

VAPEC + VAPEC Model
Multiple Thermal Plasma Volumes

Thermal + Broken Power Law Model
Thermal Plasma + Nonthermal Accelerated Particle Distribution



For this microflare, the double-thermal (VAPEC+VAPEC) model provides the best fit to the observed spectrum.

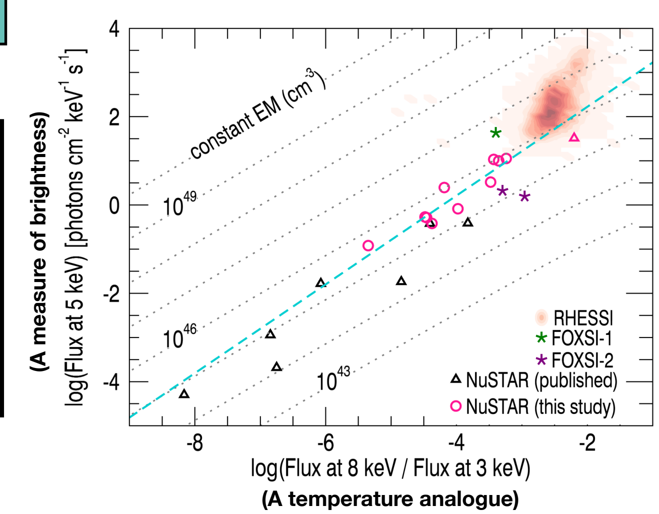
Spectral Analysis - All Results

Result	Number of Events
Dominantly Thermal Best fit: Double Thermal Model	8/11
Ambiguous (Similarly well-fit by Double Thermal and Thermal + Broken Power Law Models)	2/11
Confirmed Nonthermal [2] Best fit: Thermal + Broken Power Law Model	1/11

For both of these events, calculated nonthermal energy was an order of magnitude larger than calculated thermal energy.

Thermal vs. Nonthermal Microflare Spectra

- **Blue fit line: includes only thermal NuSTAR flares** (excludes the nonthermal event, △).
- The spectral shape of the single confirmed nonthermal event is **not anomalous when compared to others.**
- The magnitudes of these events span a transition between a regime where nonthermal emission is dominant in flare spectra, and one where any nonthermal emission present is indistinguishable from thermal emission.



Further exploration of HXR events of similar brightness is needed to characterize this transition, a crucial regime for developing an understanding of particle acceleration at the smallest scales.

References

[1] Grefenstette, B., Glesener, L., Krucker, S. et al. 2016, ApJ, 826:20
[2] Glesener, L., Krucker, S., Duncan, J., et al. 2020, ApJL, 891, L34

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