Heating and Acceleration at Galaxy Cluster Shocks: Insights from NuSTAR

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with Randall Rojas and Vivek Vankayalapati

AND Silvano Molendi, Fabio Gastaldello, Allan Hornstrup, NJ Westergaard, Greg Madjeski, Desiree Ferreira, Ming Sun, Craig Sarazin, Maxim Markevitch, Simona Giacintucci, Helen Russell, Becky Canning, Richard Mushotzky et al.
How are particles heated & accelerated during a merger?

Bullet Cluster

shock front

gas flow
Conflicting evidence so far: bow shocks

Bullet Cluster: Markevitch 2006

Abell 2146: Russell et al. 2012
How are particles heated & accelerated during a merger?

Bullet Cluster

RELIC

Shimwell+ 2015

Shimwell+ 2014

J06587-5558

gas flow

shock front

Shimwell+ 2014
Galaxy Clusters: Why *NuSTAR*?

- 18"-1’ angular resolution
- OK collecting area

**But:**
- high energy sensitivity
- low background
Clusters of Interest

- Bullet Cluster
  - 7-30 keV
  - 270 ks + 150 ks
- Abell 665
  - 4-25 keV
  - 200 ks
- Abell 2146
  - 4-25 keV
  - 260 ks
- Abell 2163
  - 4-25 keV
  - 110 ks

Shocks

Cool Core

Clustering X-ray Universe 2019, Bologna
Abell 2163

IC upper limit corresponds to a lower limit on B of 0.22 uG (T+IC) or 0.35 uG (T-map)

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Rojas+ in prep.
Abell 665: another Mach~3 shock

Chandra
~150 ks

0.7 – 2 keV

Dasadia+ 16
Abell 665: \textit{Chandra}-only vs. \textit{NuSTAR}-only
Suggestive, but need to add PSF modeling

Vankayalapati+ in prep.
Abell 2146 NuSTAR Observation (260 ks)

3-5 keV  6-10 keV  10-20 keV  Temperature Map

temperature map with color bar for kT (keV)
"NuSTAR" data reject high $kT$ of upstream shock

Abell 2146: Russell et al. 2012
Same method applied to the Bullet Cluster

$3-20\text{ keV}$

$13\text{ keV}$
Need a new method

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Rate</th>
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<tbody>
<tr>
<td>8-12 keV</td>
<td>1</td>
</tr>
<tr>
<td>12-18 keV</td>
<td>3</td>
</tr>
<tr>
<td>18-25 keV</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>30</td>
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</tbody>
</table>

Rates all tied by kT

Shock region

Chandra norm.

NuSTAR constraints

too hot

just right

too cold
Bullet Cluster: resulting temperature comparison

<table>
<thead>
<tr>
<th>Chandra SB</th>
<th>Chandra kT</th>
<th>Chandra kT</th>
<th>NuSTAR kT</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Temperature range:
- 8 keV to 10 keV
- 12 keV to 14 keV
- 16 keV to 20 keV

Color scale:
- Dark blue to dark red
Insufficient statistics in the Mach~3 region (so far)
**NuSTAR observations of extended clusters**
Take aways

• *NuSTAR* is great for measuring, and spatially resolving, high temperature gas in galaxy clusters

• $kT$s largely agree, but *NuSTAR* tends to produce less extreme temperatures

• IC emission: no detections yet
  • Abell 2163: strong limits rule out previous IC estimates
  • A665, A2146: underway, no indications of IC

• Shock measurements: not yet definitive, but strong promise
  • Abell 665: somewhat favors electron shock-heating
  • Abell 2146 & Bullet cluster: more work needed, but may be limited by *NuSTAR*’s resolution
Grin and bear the sourness
Chandra - measured temperature jump

XMM-Newton - measured pressure jump

Suzaku - measured
Coma Cluster

Focused Rays
Scattered Light
Simulated
Data
Abell 2256: kT (and IC?) features

Chandra

NuSTAR

XMM-Newton

JVLA

Claimed temperature jump

No jump seen

Cool core and cold front

Trasatti+ 2015
Ways this work can help with XRISM analysis

The NuSTAR-XRISM synergy is excellent:
- both have order 1 arcmin PSFs
- bandpasses overlap but combine for a much broader total bandpass
- both require similar tools/techniques to deal with PSF-mixing

Galaxy cluster science does not require simultaneous observations!
- assuming scattered light can be dealt with, current mosaics can be combined with future XRISM observations
- as Hitomi demonstrated so well, NuSTAR’s survival until XRISM’s launch is not guaranteed; better to begin deep, Legacy-class surveys of likely XRISM targets ASAP!

I’m trying to hire a person to do exactly this, right now!
If you or someone you know is interested in such work, please let me know!
Systematics in galaxy cluster kT measurements

Schellenberger+ 2015