Electron Heating and Acceleration at Galaxy Cluster Shocks: Insights From *NuSTAR*

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NuSTAR Observations of Galaxy Clusters

• Cluster observations and IC results so far

• Temperature measurements in the Bullet Cluster

• Temperature measurements in Abell 665

• some grumpy old man grumbling
Sample of *NuSTAR* Observations

Also the Cygnus A cluster, the Abell 754 shock, Abell 523, RX J1347 (not yet observed), and Ophiuchus (two observations for twice the price!)
Detecting Inverse Compton Emission

\[ \frac{L_R}{L_X} = \frac{B^2/(8\pi)}{aT_{CMB}^4} \]

160 Million K (14 keV)

Power Law Inverse Compton Emission

Far UV $\rightarrow$ “Soft” X-ray $\rightarrow$ “Hard” X-ray $\rightarrow$
IC Non-detections

Bullet

IC upper limit
B > 0.2 uG

Coma

Gastaldello+15

Wik+14
Abell 665

\[ kT = 7 \text{ keV} \]

\[ kT = 11 \text{ keV} \]

Vacca+ 2010
\[ \langle B \rangle \sim 0.7 \text{ uG} \]

IC upper limit
\[ B > 0.06 \text{ uG} \]
Thermal X-ray Spectra

45 Million K (4 keV)
160 Million K (14 keV)

Far UV $\rightarrow$ “Soft” X-ray $\rightarrow$ “Hard” X-ray $\rightarrow$
slower flow away from shock

Electron Temperature $T_e$, keV

$r$, arcsec

Chandra Measurements

Markevitch 06
Abell 3667 NW Relic

Sarazin+ 18
Bow Shocks: Electron-Ion Equilibration

Bullet Cluster: Markevitch et al. 2002

Abell 2146: Russell et al. 2012
Bow Shocks: Electron-Ion Equilibration

Bullet Cluster: Markevitch 2006 (de-projected)

Mach~3

Abell 2146: Russell et al. 2012 (projected)

Mach~2
Bullet Cluster

Chandra ACIS
~500 ks

0.8 – 4 keV

Shock

Cool Core

NuSTAR
270 ks

7-30 keV

Shock

Cool Core

Bullet Cluster
Spatial Modeling

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-12 keV</td>
<td>too hot</td>
</tr>
<tr>
<td>12-18 keV</td>
<td></td>
</tr>
<tr>
<td>18-25 keV</td>
<td>too cold</td>
</tr>
</tbody>
</table>

Chandra norm.  

NuSTAR constraints

too hot
just right
too cold
NuSTAR-Chandra Joint Fit Results
**NuSTAR-Chandra Joint Fit Results**

Abell 2146: Russell et al. 2012

(projected)
Spatial Fitting Results — Modified Regions

Chandra SB

Chandra kT

Chandra kT

NuSTAR kT

March 20, 2018   -   Daniel R. Wik   -   SnowCluster: Shock Temperature Measurements with NuSTAR   -   16
Due to the small extent of the Mach~3 shock, \textit{NuSTAR} cannot constrain between the two heating scenarios. Need HEX-P!

Probe class hard X-ray telescope with 15” HPD
Abell 665

Chandra ACIS

$0.7 - 2$ keV

$\sim 150$ ks

Ear1

Ear2

N

S

A

C1 (Cool Front)

C2 (Cool Front)

Dasadia+ 16
Abell 665

Chandra ACIS
~150 ks

NuSTAR
200 ks

0.7-2 keV

Ear2

N

Ear1

S

C1 (Cool Front)

C2 (Cool Front)

S1 (Shock)

915 kpc

300"

4-25 keV

Declination

Right ascension

32:00 30 31:00 30 8:30:00 30 29:00
Abell 665 Temperature Map
Abell 665 Temperature Map

Chandra

NuSTAR

$kT$ (keV)
Abell 665 Temperature Map

Cold fronts
Shock front

APEC norm (arbitrary values)
Abell 665 Temperature Map

Projected

\[ kT \text{ Jump } \sim 3x \]
\[ \text{implied Mach } \# \sim 2.5-3 \]
\[ \text{if shock heated} \]

Chandra SB jump
Mach \# \sim 3.4

De-projected (predicted)
Abell 665 Temperature Map

Projected

$kT$ Jump $\sim 3x$ implies Mach $\# \sim 2.5-3$

*if* shock heated

Chandra SB jump
Mach $\# \sim 3.4$

De-projected (predicted)
Abell 665 Temperature Map

Projected

kT Jump ~ 3x implies Mach # ~ 2.5-3
if shock heated

Chandra SB jump
Mach # ~ 3.4

De-projected (predicted)

Measured

kT (keV)

NuSTAR
(colors, dashed)

adiabatic model

Chandra (black)

Radius (kpc)
A665 kT Measurement Caveats

- No accounting for contributions of PSF scattering

- NuSTAR-only spectral fits, may be biased toward higher kTs along multi-T lines-of-sight

- Point source contamination in faint regions possible concern

- Direct deprojection fits to joint Chandra-NuSTAR spectra will provide the most accurate kT of the shock

- Shock cooler to east — Mach # variation across shock?
NuSTAR Coma Cluster Mosaic
Ophiuchus Cluster Observation

Chandra Residual
(0.6-7.5 keV)

XMM Entropy

Eastern inner cold front

Southern outer cold front

Concave discontinuity

Southern surface brightness excess

kT/ne^{2/3} (keV cm^2)

Werner+16
Ophiuchus Cluster Observation

Time of NuSTAR Observation

Counts/cm²/sec (15–50 keV)

Granat 1716–249

DAILY

Swift/BAT Transient Analysis

H. Krimm, GSFC/USRA for the BAT team

Generated Wed Nov 8 23:11:29 UTC 2017
Ophiuchus Cluster Observation

A  B
Ophiuchus Cluster Observation
Potential of Abell 2146 with NuSTAR

(a)

Region for Spectral Simulation

Shock Fronts

1 arcmin
220 npc

(b)

Simulated Upstream Shock Spectra for A and B Telescopes

Counts/s/keV

Energy (keV)
Summary

_NuSTAR_ can provide complimentary kT measurements, especially for hot clusters