Physics of the Cosmos Program
X-ray Science Interest Group

Response to Hitomi

Mark Bautz

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Chair of the X-ray Science Interest Group
Vice-Chair of the Physics of the Cosmos Program Analysis Group
Thanks to:

Rich Kelley
Jon Miller
Niel Brandt
Jack Hughes
Ralph Kraft
Knox Long
Maxim Markevitch
Richard Mushotzky
Rob Petre
Chris Reynolds
Randall Smith
Overview

• Hitomi Chronology and the Soft X-ray Spectrometer (SXS)

• Results from Hitomi SXS observation of Perseus

• X-ray Science Interest Group Response
  – Community discussion with Paul Hertz
  – White Paper on importance & timeliness of calorimeter science
Hitomi Mission & Chronology

• Major (2.7 T) JAXA/NASA high-energy astrophysics mission
  – Prime instrument: X-ray micro-calorimeter ‘integral field’ (non-dispersive) spectrometer (SXS)
  – Also: Hard X-ray Imager (10-80 kev), Soft X-ray Imager (0.3-15 keV), Soft Gamma Compton Camera (40 – 600 keV)
  – Broad international collaboration: ~60 institutions in Japan, N. America, Europe

• NASA provided SXS detectors & cooling chains, plus mirrors for SXS and SXI, all via Explorer Mission of Opportunity ($75M h/w)
  – US observers would have received 40% of observing time after PV phase
  – 10% additional time available to joint US/Japan proposals
  – NASA GO program was funded at $5M/yr (total SEO ~$46M)

• Successful Launch February 17, 2016
• First SXS observation began February 24
  – Performance (e.g. FWHM = 4.9 eV) exceeded goal (5 eV) & req’t (7 eV)
• Contact with spacecraft lost March 26
• End of Mission declared April 28
  – JAXA: Loss due to S/C faults & operational error unrelated to instruments
**Hitomi Soft X-ray Spectrometer (SXS)**

**Astro 2010: “Truly revolutionary technology”; provides**

- First high-resolution X-ray spectroscopy of extended sources → plasma velocities, precise abundances in clusters, galaxies & SNR
- Unprecedented spectral sensitivity, esp. at Fe K lines ( ~ 6 keV) → e.g., outflow velocities, mass/energy feedback from SM black holes

![Graph showing figure of merit (FoM) vs. energy for various X-ray detectors.](image)

- ~100x better velocities in clusters, SNR, starburst galaxy flows
- ~50x better velocities in AGN, stars via K shell transitions of S, Ar, Ca, Fe and Ni

FoM for weak-line velocity $M \equiv (E/\Delta E)(A_{\text{eff}}/\Delta E)^{1/2}$
Hitomi SXS spectrum of Perseus cluster

BLACK: Hitomi SXS (FWHM 4.9 eV)
BLUE: Best previous spectrum (Suzaku CCD; FWHM 140 eV)

21 July 2016
X-ray SIG for APS
Hitomi Collaboration, Nature 2016
Hitomi SXS spectrum of Perseus: FeXXV Heα

- $\sigma_{\text{turb}} = 164 \pm 10$ km s\(^{-1}\)
- $P_{\text{turb}} < 0.04 \times P_{\text{thermal}}$
- Resonant scattering?

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**Legend**

- **BLACK**: Hitomi SXS data
- **PURPLE**: Hitomi SXS line response function
- **BLUE**: Best previous spectrum (Suzaku CCD)

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Hitomi Collaboration, Nature 2016
X-ray Science Interest Group Activity

• June 8: Telecon to discuss response to loss of Hitomi
  – Paul Hertz, Rich Kelley (SXS PI), >75 participants
  – Consensus was reached on several issues (see next chart)
  – Paul Hertz requested community input on “timeliness and importance of microcalorimeter science”

• July 5: A white paper, “The Scientific Significance of the Soft X-ray Spectrometer” was released in response to Paul’s request
  – Prepared by a group of X-ray SIG volunteers
  – Broadly endorsed by X-ray SIG upon release
Summary of X-ray SIG Discussion June 8

• Meeting occurred before either JAXA or NASA had made any public comment on a response to the loss of Hitomi
  – Focus was on scientific value of re-flight, not on implementation issues

• There is XRSIG consensus that the scientific case for a recovery mission is as strong or stronger than it was for Astro-H/Hitomi
  – The XRSIG was invited to respond to Paul Hertz’s request for a white paper on this subject.

• There is XRSIG consensus that any recovery mission should launch well in advance of Athena (~5 years, i.e. by 2023) to be sensible.

• There is a great deal of community interest in understanding the viability, opportunity costs and scientific tradeoffs of a recovery mission. Lacking information, we could not address these topics.

• There is particular concern about the impact of a recovery mission on the Astrophysics Explorer program.
Overview of White Paper

• Deals only with the scientific importance and timeliness of a potential re-flight of the SXS instrument (& suitable mirror)
• Argues that “… an array of frontier scientific fields at the heart of the 2010 Decadal Survey, the NASA Physics of the Cosmos program, and the 2013 NASA Astrophysics Road map would have been transformed had the Hitomi spacecraft not been lost.”
• Finds that re-flight [of the SXS] with a launch no later than 2023 would “fulfill much of the immense scientific promise of the Hitomi SXS.”
• Finds that a re-flight would be timely as it would:
  – Overlap and create synergies with JWST, HST, NuSTAR, Chandra; Athena (to launch end of 2028) would likely not do so
  – Serve as a pathfinder for more complex instruments planned for Athena & X-ray Surveyor
Simulated SXS AGN spectrum: High-ionization wind driving molecular outflow

- Fast, highly ionized winds may drive molecular outflows in quasar-mode feedback (Tombesi+ 2015)
- SXS resolves multiple absorption features, diagnosing mass outflow, kinetic power, and SMBH role in quenching star formation
• Ratios of certain low-abundance elements (e.g. $^{58}\text{Ni}$ and $^{55}\text{Mn}$) in remnants are sensitive to Type Ia explosion channel (Yamaguchi+ 2015)
• SXS detects weak lines and constrains complex, non-equilibrium physics & velocity structure to determine accurate abundances
Synergies & Timeliness

• **Prompt SXS re-flight would overlap HST and JWST**
  – Athena (launch no earlier than late 2028) likely will not

• **UV + X-ray spectroscopy jointly probe black hole accretion & feedback physics in quasar and Seyfert phases**
  – SMBH accretion disk structure revealed in UV and X-ray
  – UV/X-ray together constrain winds and outflows (Kaastra+ ‘14)
  – SXS is first X-ray spectrometer with resolving power (E/dE ~1400 @ 6.7 keV) approaching that of HST/STIS

• **JWST + SXS would pair two extraordinary new capabilities**
  – Majority of cosmic ionizing radiation is produced in obscured environments accessible only to IR & X-ray (e.g. Tombesi+, 2015)
  – SXS would thus support JWST goal of understanding role of SMBH in galaxy evolution
  – Precise SXS cluster/SNR abundances would complement JWST measurements of abundances over cosmic time
  – SXS would trace kinematics of hot ISM in star-forming galaxies, supporting JWST goal of understanding how chemical elements are distributed in galaxies

• **SXS would serve as scientific & technical pathfinder for more complex instruments on Athena and X-ray Surveyor**
Summary: SXS science is important & timely

• The first-light Hitomi SXS observation of Perseus, when fully interpreted, will dramatically deepen our knowledge of clusters
  – Likely implications for cosmic structure formation, cluster masses, plasma excitation, elemental abundances, and atomic physics

• SXS could address a broad range of other high-priority issues identified by Astro2010 & NASA Astrophysics Roadmap, e.g.:
  – Formation & growth of SMBH & their impact on galaxy evolution
  – Flows of matter & energy in the circumgalactic medium
  – Mass-energy-chemical cycles in galaxies
  – Sub-populations of Type Ia supernovae
  – Star formation and evolution of circumstellar disks

• A prompt SXS re-flight is timely:
  – Would increase the power of HST and JWST as Athena cannot
  – Would serve as important pathfinder for Athena & X-ray Surveyor
Additional Information
# White Paper Endorsers

Table 1: Endorsements

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<tr>
<th>Name</th>
<th>Institution</th>
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*Complete as of July 11, 2016*
Hitomi SXS observation of Perseus

SXS FOV on Chandra image

- Low ICM velocity dispersion despite AGN heating, bubbles etc.
- Modest but detectable large scale motions

LOS velocity variation from SXS

21 July 2016

X-ray SIG for APS

Hitomi Collaboration, Nature 2016
Interpretation of SXS Perseus observation
(Hitomi Collaboration, 2016 Nature)

• The intracluster medium (ICM) in the center of Perseus is remarkably placid
  - Line broadening $\Rightarrow$ RMS ICM velocity $\sigma_{\text{los}} = 187 \pm 13 \text{ km s}^{-1}$ despite AGN-inflated bubbles & merger-induced cold fronts
  - $P_{\text{turb}} < 0.04 P_{\text{thermal}} \Rightarrow$ Systematic errors in “hydrostatic” mass due to ICM turbulence may be modest and can be constrained
  - Resonant-to-forbidden line ratio in FeXXV He$\alpha$ complex is low for optically thin ICM, consistent with resonant scattering, low $\sigma_{\text{los}}$
  - If turbulence is heating the ICM, it must be replenished on short timescales ($4\%$ of $t_{\text{cool}}$), so it can’t spread from the core to heat the rest of the cluster.

• $\sim 150 \text{ km s}^{-1}$ bulk velocity shear across 60 kpc observed region
  - Comparable to shear in molecular gas in core
  - Possibly a result of residual ‘sloshing’ from past merger, as expected from observed cold front

• Atomic physics (line energies & strengths) needs work