On the Scientific Significance of the Soft X-ray Spectrometer

A White Paper prepared by the X-ray Science Interest Group
of NASA's Physics of the Cosmos Program

July 5, 2016

Summary

The X-ray microcalorimeter spectrometer that flew aboard Hitomi, known as the Soft X-ray Spectrometer (SXS), delivered extraordinary results through its unparalleled spectral resolution and sensitivity. The instrument's sole observation of a line-rich X-ray source will, when fully interpreted, dramatically improve our knowledge of galaxy clusters, connecting and advancing fields as diverse as large-scale structure formation and atomic physics. 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 Roadmap would also have been transformed had the Hitomi spacecraft not been lost. This White Paper responds to a request from NASA's Astrophysics Division for a community assessment of the scientific importance and timeliness of a re-flight of the SXS. We find that a re-flight mission with a launch no later than 2023 would fulfill the immense scientific promise of the Hitomi SXS. It would overlap with the James Webb Space Telescope (launch: 2018; projected lifespan: 5-10 years) and the Hubble Space Telescope (projected end: 2026), and realize synergies with current missions at the core of NASA's strategic vision, including the hard X-ray NuSTAR mission and the sharp-imaging Chandra X-ray Observatory. In contrast, ESA's Athena, the only X-ray microcalorimeter mission currently planned, will not launch before late 2028, in all likelihood overlapping with none of these strategic NASA missions. This document aims to 1) briefly explain the history and unprecedented capabilities of X-ray microcalorimeters, 2) provide a sample of the breadth and timeliness of calorimeter science selected from a much larger set of anticipated advances, and 3) demonstrate, by reference to the Hitomi data from the Perseus cluster, the richness of the discovery space that would be re-opened by re-flying the SXS.

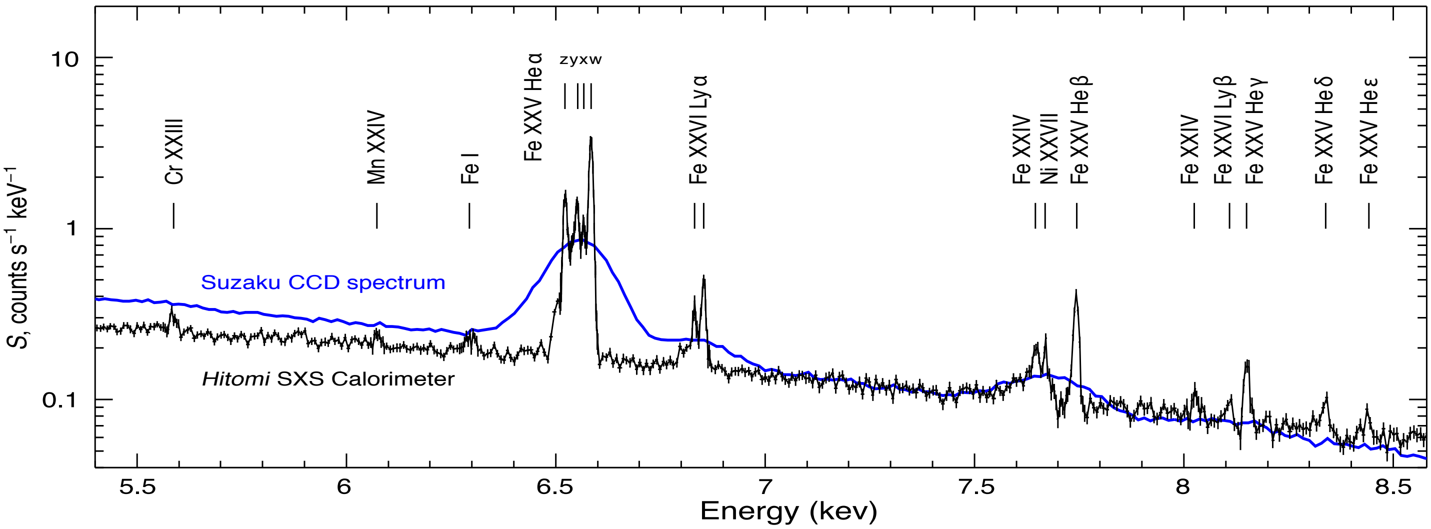

Figure 1: *A segment of the Hitomi SXS X-ray microcalorimeter spectrum of the core of the Perseus cluster (resolution: 4.9 eV; Hitomi Collaboration. 2016, Nature). The calorimeter data are shown in* **black** *with flux errors. All of the individual lines in several different complexes are separated and individually resolved for the first time. For comparison, the best prior spectrum of the Perseus core is shown in* **blue**, *from an observation with the Suzaku X-ray CCD spectrometer (resolution: 140 eV).*

I. X-ray Calorimeters

Some of the most pressing questions in modern astrophysics and cosmology, including the origin and dispersion of elements in supernovae, the effect of feedback of supermassive black holes on the evolution of their host galaxies, and the formation of structure on galaxy cluster scales - will be transformed by high-resolution X-ray spectroscopy. The technology required – the quantum microcalorimeter – is already mature. Whereas currently operating high-resolution X-ray spectrometers use slitless objective diffraction gratings and hence are essentially useful only for point sources, a microcalorimeter is a high-resolution integral field imaging spectrometer. A microcalorimeter thus provides the unprecedented capability for high- resolution spectroscopy of extended X-ray sources, notably clusters of galaxies, star-forming galaxies, and supernova remnants. Morevover, the microcalorimeter's excellent and nearly energy-independent intrinsic spectral resolution (a few eV at 6000 eV) results in spectral resolving power that increases with energy, complementing that of grating spectrometers and providing unmatched resolving power and sensitivity at X-ray energies in the 2-12 keV band (see Figure 2), where the all-important diagnostic K-shell lines of many elements are found.

The X-ray quantum calorimeter was conceived in 1982 at the Goddard Space Flight Center and was successfully proposed for the AXAF mission in 1985 (the top priority of the 1980 Decadal Survey). The idea was to use infrared bolometer technology to make a non-dispersive, single-photon-X-ray detector with extremely high spectral resolution. The calorimeter was not included in the final AXAF mission (later renamed Chandra) due to budget pressure and the higher priority assigned to high-resolution imaging. In the fall of 1993, however, NASA and ISAS agreed that the calorimeter would be included as part of the next Japanese mission, Astro-E. After successful development of the calorimeter instrument and integration into the satellite, a rocket failure in February 2000 led to the loss of Astro-E. Recognizing the crucial scientific importance of the calorimeter, ISAS and NASA approved a recovery mission (Astro-E2, later named Suzaku) and launched it in July 2005. The calorimeter performance was excellent during initial checkout, but - before any astrophysical data were obtained - the cryostat failed due to a spacecraft design error, rendering the calorimeter inoperable.

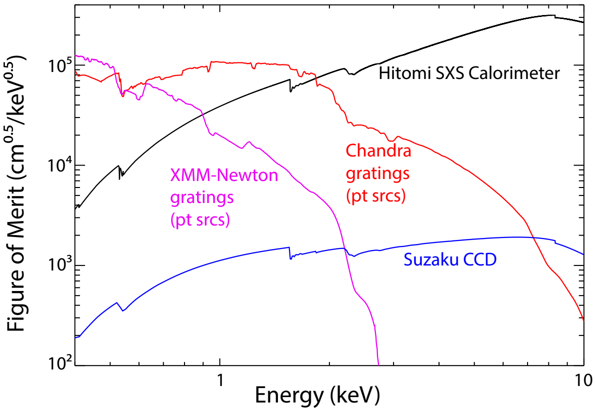

Figure 2: *The figure of merit for measuring the velocity of a weak emission or absorption line as a function of energy for the imaging spectrometers such as the Hitomi SXS calorimeter and a Suzaku CCD, along with the equivalent values for point sources observed with Chandra and XMM-Newton gratings. For extended sources, the SXS is 100 times more sensitive to Fe-K velocity diagnostics emission than current technologies (CCDs).*

Most recently, the Soft X-Ray Spectrometer (SXS), incorporating a calorimeter array, was launched as the prime instrument on the JAXA Astro-H (Hitomi) observatory. Only 7 days after launch on 17 February, 2016, the SXS obtained its first astrophysical data, an observation of the core of the Perseus cluster. The SXS operated flawlessly. A resolution of 4.9 eV was achieved at 6 keV, exceeding the SXS performance goal, and surpassing the resolution of any previous non-dispersive X-ray spectrometer at that energy by more than a factor of 25. Just a few days of exposure on Perseus produced an extraordinary data set (described later in this White Paper). Further, on-orbit measurements of the liquid He cryogen depletion rate indicated that the primary operational lifetime would have been ~4 years, and this would have been followed by a cryogen-free mode that would have continued to deliver high-resolution spectra with only slightly reduced observational efficiency.

Tragically on day 38 of the mission, a cascade of hardware, software, and human errors associated with the attitude control system (as acknowledged by JAXA, and having no connection to the SXS) resulted in physical loss of the spacecraft. JAXA declared an end of operations on April 28, 2016.

The science of high-resolution X-ray spectroscopy has been highly ranked by three of the past four decadal surveys, reaffirmed by the 2013 NASA Astrophysics Visionary Roadmap, and has motivated three attempted flights. The few days of data from the Perseus cluster observation have already produced a Nature paper (Hitomi Collaboration 2016), and at least eight other papers based on this observation are in preparation. The data obtained represent less than 1/1000th of the hoped for data from Hitomi. The potential richness of this science has never been clearer.

II. Scientific Breadth, Synergies, and Timeliness

A re-flight of the SXS* would address a broad range of scientific problems at the core of NASA's Science Plan and at the frontiers identified by both the 2010 Decadal Survey New Worlds, New Horizons (NWNH) and 2013 NASA Astrophysics Visionary Roadmap Enduring Quests, Daring Visions. At the very largest mass scales, NWNH's top-priority questions on cosmic origins, including "How did cosmic structure form and evolve?" and "What are the connections between dark and luminous matter?" would both be addressed through SXS observations of the hot intracluster medium, greatly reducing systematic uncertainties in cluster masses and, for the first time, powerfully challenging predictions of ICM kinematics inferred from simulations of cosmic structure and cluster formation. At the smallest mass scales, the unprecedented sensitivity of the SXS to coronal plasma diagnostics and kinematics would provide new insight into the abiding NWNH questions "How do stars form?" and "How do circumstellar disks evolve?". In between, as we discuss below, SXS observations of active galactic nuclei (AGN), galaxies, and supernova remnants (SNR) will address other compelling NWNH questions.

The scientific overlap between a re-flight of the SXS and the powerful new observatories of the next decade is very strong. The SXS could look deep into star-forming galaxies to characterize the hot phase of the ISM, and, in concert with ALMA's exquisite sensitivity to the cold phase, strongly constrain starburst models (Tombesi et al. 2015). Precise SXS measurements of the elemental abundances in clusters and supernova remnants would complement JWST measurements of abundances over cosmic time. SXS measurements of the winds from active galaxies would, in combination with NuSTAR spectra, determine the total mass flux and energy from them to provide a direct comparison with AGN feedback models (Nardini et al. 2015). The synergies between the SXS and these facilities and others (including WFIRST, LSST and TMT) underscore both the importance and timeliness of a prompt SXS re-flight. Absent a re-flight, the next X-ray microcalorimeter will not be available until the planned launch of Athena in late 2028, in all likelihood after HST, NuSTAR, and possibly even JWST have ceased operations. Further, an SXS re-flight would serve as an invaluable pathfinder for the much more complex microcalorimeter instruments planned for Athena and X-ray Surveyor.

An SXS re-flight would have many potential targets, as scores of galaxy clusters, galaxies, AGN, SNR, X-ray binaries and stars are bright enough to study in detail in reasonable exposures. We estimate from the White Papers written for Hitomi† that more than 500 objects would be observed over a 5-year mission. In the following sections we highlight just a few of the many fields that would be profoundly changed by a re-flight of the SXS.

II.a Active Galactic Nuclei and Black Holes

One of the most important discoveries of extragalactic astronomy in the past two decades is that supermassive black holes are major players in the story of galaxy evolution, stifling or even entirely stopping the growth and evolution of massive galaxies. This remarkable finding motivates the NASA Physics of the Cosmos goal to "Understand the formation and growth of massive black holes and their role in the evolution of galaxies," and the 2010 Decadal Survey Survey question, "How do black holes grow, radiate, and influence their surroundings?" X-ray and UV absorption spectra obtained with Chandra, XMM-Newton and HST find that winds are present in about 50% of AGN, and that typical velocities are in the few 100-1000 km s^{-1} range. However, recent results suggest that the true agents of feedback may be fast (0.1-0.3c), high-column-density, very high-ionization outflows that, briefly, inject enormous energies and momenta into galaxies during special evolutionary phases (Chartas et al. 2002, Nardini et al. 2015). While these components may be the dominant terms in the energy budget of the active galaxy and likely drive the galactic-scale molecular outflows that actually shut down star formation, they only reveal themselves in X-ray absorption lines of iron and nickel above 6 keV (Tombesi et al. 2015). A robust characterization of these important, possibly multi-component, high-ionization winds absolutely requires high-resolution, high-throughput spectroscopy at E > 4 keV, uniquely possible with a calorimeter (see Figure 3).

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[*] The Hitomi SXS was a focal plane instrument. Here, by 're-flight of the SXS' we mean re-flight of that instrument together with an X-ray mirror assembly featuring performance comparable to that of the Hitomi SXS mirror.

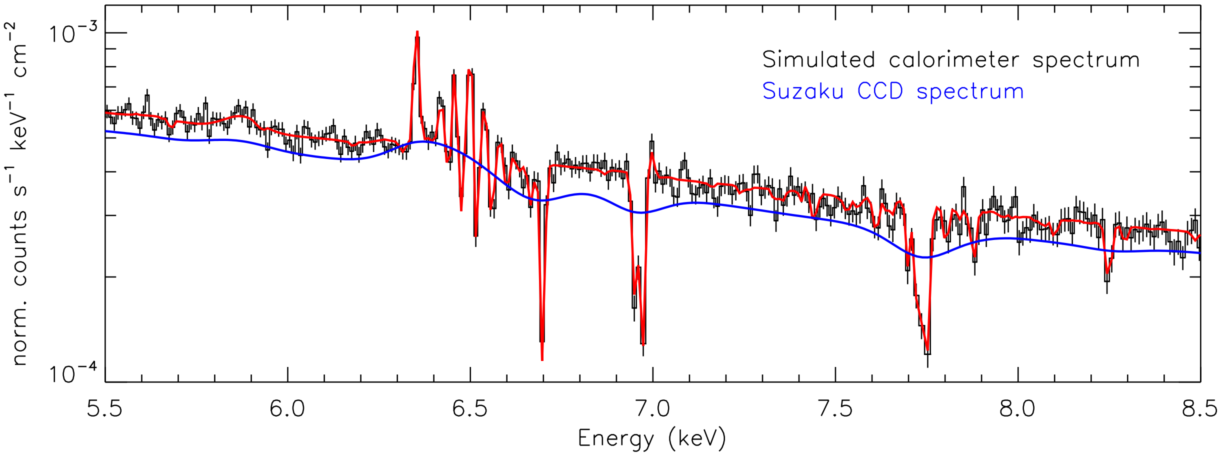

Figure 3. *A simulated Hitomi calorimeter (SXS) spectrum of the active galactic nucleus MCG-6-30-15 (data from a simulated 250ks exposure in* **black***, model spectrum in* **red***). Absorption lines (FeXXV-He-α, FeXXVI-Lyα, FeXXV He-β, FeXXVI Lyβ, and FeXXVI-Lyγ) from a high ionization, fast (2000 km s^{-1}) wind component are clearly visible, as is a weak neutral iron fluorescence emission line from the molecular torus surrounding the central engine. When viewed with CCD resolution (***blue** *line), this spectral structure and the wind properties it conveys (mass outflow rate, kinetic power, role in feedback) are inaccessible.*

II.b Starburst galaxies

Nearby starburst galaxies are the local analogs of the systems at high redshift that account for most of the star formation and metal production in the Universe. Their poorly understood hot galactic superwinds eject a significant fraction of the metals synthesized in the starburst into the circum- and inter-galactic medium (IGM) (e.g., Borthakur et al. 2013; Veilleux, Cecil, & Bland-Hawthorn 2005). Understanding the feedback from superwinds, along with AGN outflows, would directly address the 2010 Decadal Survey's Cosmic Order questions, "What are the flows of matter and energy in the circumgalactic medium?" and "What controls the mass-energy-chemical cycles within galaxies?" The crucial, missing link is the complete characterization of the outflowing X-ray plasma (its composition, ionization, and velocity) to demonstrate that it escapes the galaxy.

UV/optical data show entrained cool gas in starburst galaxies with velocities between 200-1000 km s^{-1} (e.g., Strickland et al. 2009), near but below the galactic escape velocity. An X-ray microcalorimeter would directly measure the abundances, temperature, ionization state, and Doppler shifts in the hotter, escaping gas and distinguish the physical origin of the wind; e.g., shocked, photoionized and collisionally excited gas. Given sufficient signal-to-noise ratio, as demonstrared by the Hitomi data from the Perseus Cluster, a microcalorimeter can detect shifts of ΔE ~ 1 eV, or v ~ 300 km s^{-1} at 1 keV and v>50 km s^{-1} at 6 keV (Hitomi collaboration 2016), easily sufficient to trace the ejected metals. The same capabilities enable comparison of the hot halos in normal spiral galaxies with those in their more active counterparts. Abundance ratios and the ionization state of the plasma will show whether the halos originate in a galactic fountain or mild outflow, or are the result of accretion from the IGM (Li et al. 2006).

II.c Supernovae and Supernova Remnants

Supernovae of all types play a vital role in recycling material within galaxies. By synthesizing the chemical elements, they provide the materials necessary for stars, Earth-like planets, and organic chemistry and life. In this sense, X-ray spectroscopy of SNe and their remnants directly addresses the 2013 NASA Astrophysics Roadmap theme, "Stellar Life Cycles and the Evolution of the Elements," and the 2010 Decadal Survey questions, "How do the lives of massive stars end?" and "What controls the mass-energy-chemical cycles within galaxies?"

Supernovae also play a central role in understanding the rate of cosmic acceleration, as Type Ia supernovae serve as distance indicators (Riess et al. 1998, Perlmutter et al. 1999). Optimum use of SNe Ia for cosmology requires understanding the

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[†] The 18 Astro-H White Papers are available at arXiv:14121162 through 14121179.

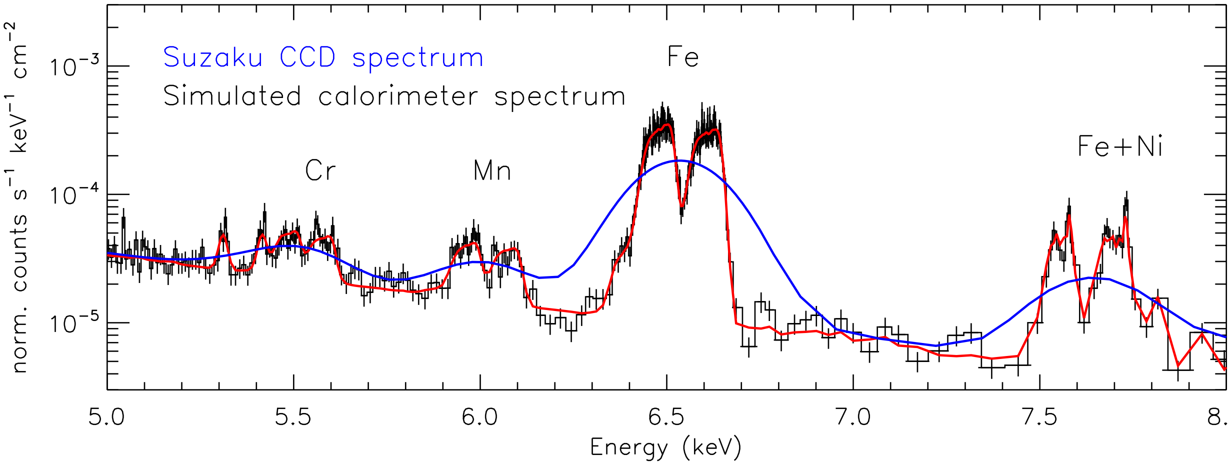

Figure 4. *An X-ray microcalorimeter will easily measure the abundance of rare elements in supernova remnants (e.g., Cr, Mn, and Ni at 5.6, 6.1, and 7.6 keV, respectively), while at the same time constraining the thermodynamic state, line broadening, and bulk motion flows of these species. The Suzaku CCD spectrum (resolution: 140 eV) of the SN Ia remnant 3C 397 is shown in* **blue** *(e.g., Yamaguchi et al. 2015), a simulated Hitomi spectrum (resolution: 4.7 eV) is shown in* **black**, *and the plasma model is shown in* **red**. *The model here (in agreement with, but not uniquely indicated by, the Suzaku spectrum) consists of two Doppler-shifted plasma models separated by 6000 km s^{-1} to represent the approaching and receding hemispheres of the SNR, with each component broadened by 600 km s^{-1} to account for thermal and turbulent broadening. Whereas the CCD spectrum only provides basic measurements of line widths, centroids, and intensity, the microcalorimeter spectrum allows for the measurement of relevant astrophysical quantities (e.g., elemental abundances, electron temperature, ionization states, expansion velocities, ion temperatures, and turbulence) that will reveal the role of single- and double-degenerate channels for SN Ia cosmology.*

subpopulations - the single-degenerate (one white dwarf accreting from a normal star) and double-degenerate (a massive white dwarf accreting from a less massive white dwarf) channels. Supernova light curves offer little insight into these populations; in contrast, X-ray spectroscopy provides a path forward.

The single-degenerate channel is expected to be driven by the explosion of Chandrasekhar-mass white dwarfs with higher core densities, leading to higher rates of the neutronized species ^{58}Ni and ^{55}Mn. These elements are very difficult to detect with CCD spectrometers (the brightest Ni line is blended with Fe; see Figs. 1 & 4), and additionally the interpretation of the observed line ratios as relative abundance ratios (which is the relevant quantity for comparison with theory) is made difficult by the astrophysical complexity of supernova remnants. In remnants, we observe non-solar elemental abundances, non-equilibrium conditions (i.e., the timescales for dynamical changes are comparable to the timescales for thermodynamic state changes), and multiple emission mechanisms, all of which can vary with position and time (on a timescale relevant to a graduate student's thesis) in a single object! Given this extreme astrophysical complexity the value of high spectral resolution cannot be overstated; with so many degrees of freedom in the spectral models we need as many independent spectral bins as possible.

CCD spectra are limited to resolving the lines of astrophysically abundant species (yielding intensity, centroid, and width measurements), separating He-like and H-like charge states, and diagnosing broad emission mechanisms (thermal vs. nonthermal). At SXS resolution we resolve the instrumentally broadened lines seen in CCDs into Doppler-shifted components, line complexes of individual charge states, and thermal broadening (see Fig. 4). Hints of the importance of the Fe-group elements in understanding the subpopulations within Ia SNe have emerged from deep Suzaku CCD observations of the SN Ia remnants Tycho (Badenes, Bravo, & Hughes 2008), Kepler (Park et al 2013), and 3C 397 (Yamaguchi et al. 2015; see Fig. 4) that show strong lines from neutron-rich species (Mn and Ni). But the interpretation of the line ratios as relative abundance ratios depends strongly on measuring the thermodynamic state of the plasma. With the current CCD spectra, simple parameterized models are used to constrain the electron temperature and ionization state; the derived elemental abundance ratios are therefore

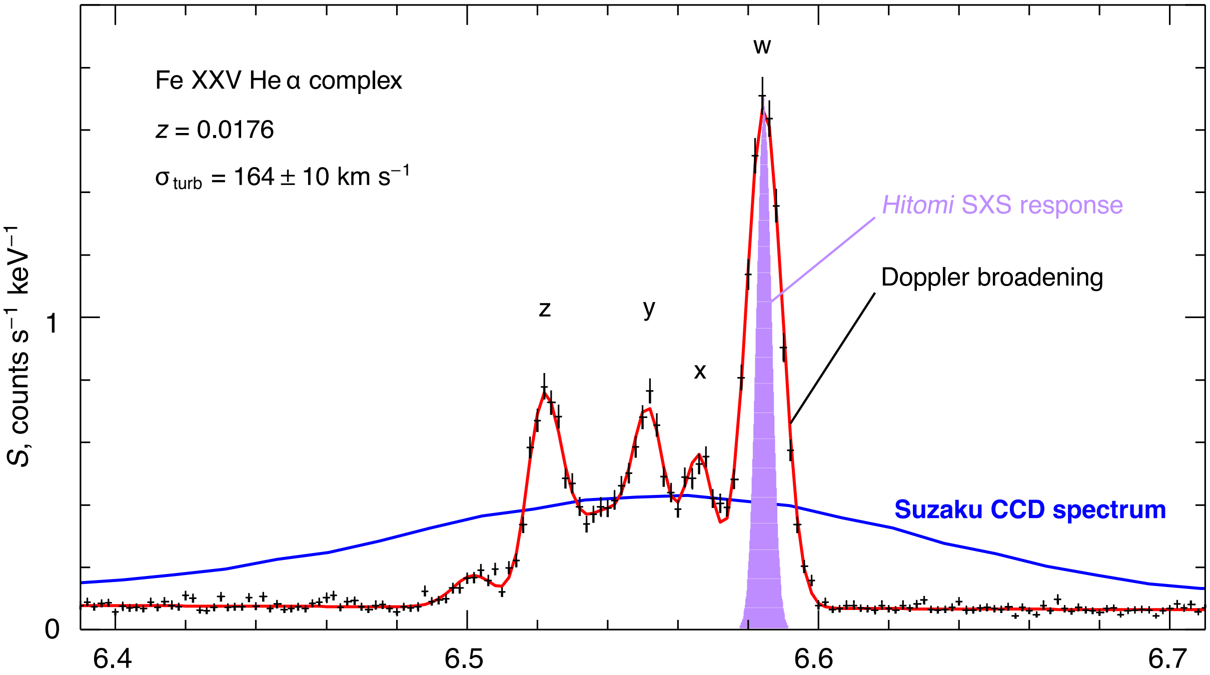

Figure 5. *The Hitomi X-ray calorimeter (SXS) spectrum of the core of the Perseus cluster is shown (***black** *data points with flux errors). The Fe XXV He-α emission line complex is produced by hot gas in the cluster core, and is a direct trace of the local physics. The* **magenta** *line depicts the 4.7 eV resolution of the calorimeter. The best model for the data is shown in* **red***; the difference between the model and the instrument resolution measures the turbulent motion of the gas in the cluster core (thermal broadening is subdominant). This is only possible because the Hitomi SXS calorimeter has resolved the Fe XXV He-α emission line complex into its major components and resolved the width of each component. For comparison, the previous-best spectrum of this line complex in the Perseus core, obtained using X-ray CCD spectrometers aboard Suzaku (resolution: 140 eV), is shown in* **blue**.

subject to the strong assumptions that go into the parameterized models. SXS spectra would largely eliminate these uncertainties by allowing for model-independent analyses, while also accounting for separate Doppler components and thermal broadening, yielding important new information on the heating processes in the SNR ejecta. There are dozens of other remnants in the Galaxy and Magellanic Clouds that are bright enough to allow similar studies with a re-flight of the SXS.

The sensitivity of the SXS to lines from low-abundance elements, together with its capability to resolve the complex, non-equilibrium physical conditions in remnants, would therefore open the way to a new understanding of the subpopulations within Type Ia supernovae. In this way, SXS spectroscopy of remnants of these events would directly address the 2010 Decadal Survey question, "What are the progenitors of Type Ia supernovae and how do they explode?"

III. Galaxy Clusters and the *Hitomi* Observations of the Perseus Cluster

The most striking demonstration of the power of X-ray calorimeter science is Hitomi's extraordinary first-light observation of the Perseus galaxy cluster, completed shortly before the spacecraft was lost.

Since the earliest days of X-ray astronomy, it has been known that the bulk of the baryonic matter in a galaxy cluster is in a tenuous, hot (10-100 million K) atmosphere of plasma that traces the gravitational potential of the dark matter, the dominant but invisible mass component. This intracluster medium (ICM) is heated by violent cluster mergers – the most energetic events in the Universe since the Big Bang, dissipating up to 10^{63} ergs of kinetic energy over a Gigayear timescale. Mergers generate shocks and copious amounts of turbulence, which convert the kinetic energy into heat, accelerate particles, and amplify magnetic fields in the ICM.

Since galaxy clusters collapse from rare cosmological density fluctuations, their total mass function and its evolution over cosmic time depend sensitively on fundamental cosmological parameters, in a manner complementary to studies based on the CMB, SNe Ia, and baryon acoustic oscillations. The mass function can be derived by studying the ICM in large samples of clusters using X-rays and the microwave Sunyaev-Zeldovich (SZ) effect – two complementary probes of the hot plasma. Locally, the ICM is the lifeblood of a cluster – it is the reservoir from which gas cools and builds up the central giant elliptical galaxy, the agent that strips bare infalling gas-rich galaxies, and the repository for all of the energy and metals ejected from member galaxies. The importance of the ICM has motivated enormous observational efforts over the past 40 years to characterize its temperature, density and abundance structure, its interaction with the central AGN, and its properties during cluster mergers.

The dynamics of the ICM, however, while of central importance to so many aspects of galaxy cluster physics, have remained very poorly understood because no X-ray spectrometer has been capable of precisely measuring Doppler shifts of the emission lines from extended objects. The SXS can do just this, tracing the injection and dissipation of bulk kinetic energy supplied by infall and feedback processes, and thereby providing information that cannot be obtained from the collisionless dynamics of the member galaxies, gravitational lensing, or SZ measurements of the integrated thermal pressure. Knowledge of ICM dynamics across the population of clusters is also crucial to understanding and reducing systematic uncertainties in cluster mass measurements. This information is essential to exploiting the full power of forthcoming large X-ray and SZ cluster samples to constrain cosmological parameters. Moreover, spatially resolved high-resolution X-ray spectroscopy of thermal line emission from all of the abundant elements determines chemical abundances with unprecedented precision. The abundances encode the nucleosynthetic history of the galaxies, and carry the imprint of feedback and transport processes driven by star formation and accretion onto supermassive black holes.

Hitomi's first-light observation of the Perseus cluster was made while the SXS detector was still shielded by a protective window that blocked low-energy photons. The data were obtained while the instrument was still reaching thermal equilibrium, and before normal calibration procedures had begun. Despite all of these limitations, this first glimpse of a high-resolution spectrum of a galaxy cluster places the transformational potential of the SXS beyond any doubt.

The observation was centered on the cool core of the Perseus Cluster, a site where all the physical processes that govern cluster evolution combine. The gas is dense and its X-ray radiative cooling time is short. However, as in other cool-core clusters, the expected runaway cooling of the gas is not observed, so some heating process must precisely balance the cooling. Several mechanisms have been proposed, including injection of mechanical energy by relativistic jets from the central supermassive black hole (the currently favored "AGN feedback"), sloshing of the gas in the core caused by gravitational disturbance from past cluster collisions, and heating by relativistic ions (cosmic rays). All three processes are present in Perseus – jets from the AGN in the central giant elliptical galaxy NGC1275 produce prominent cavities in the ICM, sloshing produces cold fronts seen throughout the cluster, and relativistic electrons are seen through their radio synchrotron emission throughout the core.

The Hitomi Perseus spectrum contains lines from many other ions and transitions (e.g., up to at least $1s^2$ – $1s6p$ for Fe in the He-like charge state!). These are a treasure trove for studies of ICM enrichment and they probe subtle physical effects such as the influence of charge exchange and non-thermal electrons on the spectral emissivity of the plasma. On the technical side, the spectrum has already revealed a large number of inaccuracies in emission line energies and fluxes in current plasma codes, and will be used to correct those. Several of the papers beyond the accepted *Nature* paper are in the works already, all from a first-light observation.

The first two phenomena, jets and sloshing, are expected to stir the gas in the core vigorously, driving turbulence on the scale of the bubbles (for AGN feedback) or on the scale of the whole core (for sloshing) that would cascade to smaller scales and dissipate, heating the gas and accelerating cosmic rays. However, the first thing that strikes the eye when one looks at the 6.7 keV Fe He-α line complex in the Hitomi spectrum (Fig. 4) is the narrowness of the lines. For the region of the core excluding the most prominent bubbles, the line-of-sight turbulent broadening is only 164±10 km s^{-1} (all quoted results are from Hitomi Collaboration 2016). For the region including the bubbles, the broadening is only slightly higher, 190 km s^{-1} . In hydrodynamic simulations that resolve the cluster cores, such levels of turbulence come from sloshing alone, without any bubbles, so the modest level of the observed motions is surprising. The turbulent pressure in the gas is only 4% of its thermodynamic pressure; thus even this continuously-stirred location in a cluster appears to be near hydrostatic equilibrium. This is extremely encouraging for using clusters as cosmological probes, but deeply puzzling for cluster physics.

In addition, the Hitomi observation reveals a gradient of the line-of-sight gas velocity of 150 km s^{-1} across the core, demonstrating the imaging power of the SXS. Comparison of the fluxes in different components of the Fe line complex with plasma models and laboratory measurements also reveals a suppression of the resonance line (marked "w" in Fig. 5), suggesting the presence of resonant scattering of that line. The effect is in broad agreement with the expectation for the observed low level of turbulence; modeling of the resonant line profile will provide detailed complementary information on the spatial structure of the ICM velocities.

IV. Conclusion

A re-flight of the Hitomi Soft X-ray Spectrometer would have enormous impact on a broad range of astrophysical problems. Many of these problems were assigned high priority by the 2010 Decadal Survey, and all of them are pressing today. As the examples presented here demonstrate, an X-ray microcalorimeter can provide insight attainable by no other means. For this reason, the data furnished by a re-flight of the instrument is needed as much today as it was when these questions were articulated in NWNH. Indeed, astrophysical progress in the current decade has only made it clearer that high-resolution X-ray microcalorimeter spectroscopy is essential for further progress on many of these questions, progress that would be delayed until late in the next decade unless the SXS is flown again. A re-flight would also be timely by enabling synergies with JWST, Chandra, and HST, and possibly other observatories (for example, NuSTAR and eROSITA), and by serving as a pathfinder for the more complex microcalorimeter instrument envisioned for Athena. In contrast, Athena will likely rely on HST and JWST archival data taken years before its launch. Finally, the first look at the SXS Perseus spectrum has already revealed a data set far richer than anticipated, offering a brief but compelling glimpse of a vast discovery space that an SXS re-flight would readily explore in depth. The X-ray Science Interest Group strongly affirms that such an endeavor would be broadly and deeply scientifically important, timely, and exciting.

V. References

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VI. Endorsers

This document was developed following a teleconference involving more than 75 members of the X-ray Science Interest Group (XRSIG). In the course of this conference, NASA Astrophysics Division Director Paul Hertz requested prompt community input on the current importance and timelines of X-ray microcalorimeter science. A group of volunteers prepared this White Paper in response to this request and on behalf of the XRSIG. Table 1 lists the names of XRSIG members and others who have endorsed it as of this writing.

Table 1: Endorsements*

Name	Institution
Kevork Abazajian	University of California, Irvine
Steve Allen	Stanford University
Marshall Bautz	Massachusetts Institute of Technology
Roger Blandford	Stanford University
Niel Brandt	The Pennsylvania State University
Laura Brenneman	Smithsonian Astrophysical Observatory
Esra Bulbul	Massachusetts Institute of Technology
Paolo Coppi	Yale University
Abe Falcone	Pennsylvania State University
Keigo Fukumura	James Madison University
George Fuller	University of California, San Diego
Jessica Gaskin	NASA's Marshall Space Flight Center
Catherine Grant	Massachusetts Institute of Technology
Richard Griffiths	University of Hawaii at Hilo
Ralf Heilmann	Massachusetts Institute of Technology
Craig Heinke	University of Alberta (Canada)
John Hughes	Rutgers University
Michael Juda	Smithsonian Astrophysical Observatory
Margarita Karovska	Smithsonian Astrophysical Observatory
Caroline Kilbourne	NASA's Goddard Space Flight Center
Dong-Woo Kim	Smithsonian Astrophysical Observatory
Ralph Kraft	Smithsonian Astrophysical Observatory
Alexander Kusenko	University of California, Los Angeles
Maurice Leutenegger	NASA's Goddard Space Flight Center
Knox Long	Space Telescope Science Institute
Dan McCammon	University of Wisconsin
Randall McEntaffer	Pennsylvania State University
Barry McKernan	CUNY/AMNH
Greg Madejski	Stanford University
Maxim Markevitch	NASA's Goddard Space Flight Center
Eric Miller	Massachusetts Institute of Technology
Jon Miller	University of Michigan
Richard Mushotzky	University of Maryland
Paul Nulsen	Smithsonian Astrophysical Observatory
Frits Paerels	Columbia University
Thomas Pannuti	Morehead State University
Sangwook Park	University of Texas at Arlington
Paul Plucinsky	Smithsonian Astrophysical Observatory
Christopher Reynolds	University of Maryland
Richard Rothschild	University of California, San Diego
Gregory Sivakoff	University of Alberta (Canada)
Randall Smith	Smithsonian Astrophysical Observatory
Francesco Tombesi	University of Maryland
Alexey Vikhlinin	Smithsonian Astrophysical Observatory
Jan Vrtilek	Smithsonian Astrophysical Observatory
Martin Weisskopf	NASA's Marshall Space Flight Center
Nick White	Universities Space Research Association
William W. Zhang	NASA's Goddard Space Flight Center

*Complete as of July 20, 2016