Concept of the X-ray Astronomy Recovery Mission

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Makoto Tashiro, Hironori Maejima, Kenichi Toda, Richard Kelley, Lillian Reichenthal, James Lobell, Robert Petre, Matteo Guainazzi, Elisa Costantini, Mark Edison, Ryuichi Fujimoto, Martin Grim, Kiyoshi Hayashida, Jan-Willem den Herder, Yoshitaka Ishisaki, Stéphane Paltani, Kyoko Matsushita, Koji Mori, Gary Sneiderman, Yoh Takei, Yukikatsu Terada, Hiroshi Tomida, Hiroki Akamatsu, Lorella Angelini, Yoshitaka Arai, Hisamitsu Awaki, Lurli Babyk, Aya Bamba, Peter Barfknecht, Kim Barnstable, Thomas Bialas, Branimir Blagojevic, Joseph Bonafede, Clifford Brambora, Laura Brenneman, Greg Brown, Kimberly Brown, Laura Burns, Edgar Canavan, Tim Carnahan, Meng Chiao, Brian Comber, Lia Corrales, Cor de Vries, Johannes Dercksen, Maria Diaz-Trigo, Tyrone Dillard, Michael DiPirro, Chris Done, Tadayasu Dotani, Ken Ebisawa, Megan Eckart, Teruaki Enoto, Yuichiro Ezoe, Carlo Ferrigno, Yasushi Fukazawa, Yutaka Fujita, Akihiro Furuzawa, Luigi Gallo, Steve Graham, Liyi Gu, Kohichi Hagino, Kenji Hamaguchi, Isamu Hatsukade, Dean Hawes, Takayuki Hayashi, Cailey Hegarty, Natalie Hell, Junko Hiraga, Edmund Hodges-Kluck, Matt Holland, Ann Hornschemeier, Akio Hoshino, Yuto Ichinohe, Ryo Iizuka, Kazunori Ishibashi, Manabu Ishida, Kumi Ishikawa, Kosei Ishimura, Bryan James, Timothy Kallman, Erin Kara, Satoru Katsuda, Steven Kenyon, Caroline Kilbourne, Mark Kimball, Takao Kitaguti, Shunji Kitamoto, Shogo Kobayashi, Takayoshi Kohmura, Shu Koyama, Aya Kubota, Maurice Leutenegger, Tom Lockard, Mike Loewenstein, Yoshitomo Maeda, Lynette Marbley, Maxim Markevitch, Hironori Matsumoto, Keiichi Matsuzaki, Dan McCammon, Brian McNamara, Joseph Miko, Eric Miller, Jon Miller, Kenji Minesugi, Ikuyuki Mitsuishi, Tsunefumi Mizuno, Hideyuki Mori, Koji Mukai, Hiroshi Murakami, Richard Mushotzky, Hiroshi Nakajima, Hideto Nakamura, Shinya Nakashima, Kazuhiro Nakazawa, Chikara Natsukari, Kenichiro Nigo, Yusuke Nishioka, Kumiko Nobukawa, Masayoshi Nobukawa, Hirofumi Noda, Hirokazu Odaka, Mina Ogawa, Takaya Ohashi, Masahiro Ohno, Masayuki Ohta, Takashi Okajima, Atsushi Okamoto, Michitaka Onizuka, Naomi Ota, Masanobu Ozaki, Paul Plucinsky, F. Scott Porter, Katja Pottschmidt, Kosuke Sato, Rie Sato, Makoto Sawada, Hiromi Seta, Ken Shelton, Yasuko Shibano, Maki Shida, Megumi Shidatsu, Peter Shirron, Aurora Simionescu, Randall Smith, Kazunori Someya, Yang Soong, Yasuharu Suagawara, Andy Szymkowiak, Hiromitsu Takahashi, Toru Tamagawa, Takayuki Tamura, Takaaki Tanaka, Yuichi Terashima, Yohko Tsuboi, Masahiro Tsujimoto, Hiroshi Tsunemi, Takeshi Tsuru, Hiroyuki Uchida, Hideki Uchiyama, Yoshihiro Ueda, Shinichiro Uno, Thomas Walsh, Shin Watanabe, Brian Williams, Rob Wolfs, Michael Wright, Shinya Yamada, Hiroya Yamaguchi, Kazutaka Yamaoka, Noriko Yamasaki, Shigeo Yamauchi, Makoto Yamauchi, Keiichi Yanagase, Tahir Yaqoob, Susumu Yasuda, Nasa Yoshioka, Jaime Zabala, Zhuravleva Irina, "Concept of the X-ray Astronomy Recovery Mission," Proc. SPIE 10699, Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, 1069922 (6 July 2018); doi: 10.1117/12.2309455

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Concept of X-ray Astronomy Recovery Mission

Makoto Tashiro[a,k], Hironori Maejima[a], Kenichi Toda[a], Richard Kelley[b], Lillian Reichenthal[b], James Lobell[b], Robert Petre[b], Matteo Guainazzi[c], Elisa Costantini[d], Mark Edison[b], Ryuichi Fujimoto[e], Martin Grim[d], Kiyoshi Hayashida[f], Jan-Willem den Herder[d], Yoshitaka Ishisaki[g], Stephane Paltani[h], Kyoko Matsushita[i], Koji Mori[j], Gary Sneiderman[b], Yoh Takei[a], Yukikatsu Terada[k], Hiroshi Tomida[a], Hiroki Akamatsu[d], Lorella Angelini[b], Yoshitaka Arai[a], Hisamitsu Awaki[l], Iurii Babyk[m,au], Aya Bamba[n], Peter Barfknecht[b], Kim Barnstable[b], Thomas Bialas[b], Branimir Blagojevic[b], Joseph Bonafede[b], Clifford Brambora[b], Laura Brenneman[o], Greg Brown[p], Kimberly Brown[b], Laura Burns[b], Edgar Canavan[b], Tim Carnahan[b], Meng Chiao[b], Brian Comber[b], Lia Corrales[q], Cor de Vries[d], Johannes Dercksen[d], Maria Diaz-Trigo[r], Tyrone Dillard[b], Michael DiPirro[b], Chris Done[s], Tadayasu Dotani[a], Ken Ebisawa[a], Megan Eckart[b], Teruaki Enoto[t], Yuichiro Ezoe[g], Carlo Ferrigno[h], Yutaka Fujita[f], Yasushi Fukazawa[u], Akihiro Furuzawa[v], Luigi Gallo[w], Steve Graham[b], Liyi Gu[x], Kohichi Hagino[y], Kenji Hamaguchi[b], Isamu Hatsukade[j], Dean Hawes[b], Takayuki Hayashi[b], Cailey Hegarty[b], Natalie Hell[p], Junko Hiraga[z], Edmund Hodges-Kluck[b], Matt Holland[b], Ann Hornschemeier[b], Akio Hoshino[b], Yuto Ichinohe[aa], Ryo Iizuka[a], Kazunori Ishibashi[ab], Manabu Ishida[a], Kumi Ishikawa[a], Kosei Ishimura[ac], Bryan James[b], Timothy Kallman[b], Erin Kara[ad], Satoru Katsuda[k], Steven Kenyon[b], Caroline Kilbourne[b], Mark Kimball[b], Takao Kitaguchi[x], Shunji Kitamoto[aa], Shogo Kobayashi[i], Takayoshi Kohmura[y], Shu Koyama[aa], Aya Kubota[ae], Maurice Leutenegger[b,ad], Tom Lockard[p], Mike Loewenstein[b], Yoshitomo Maeda[a], Lynette Marbley[b], Maxim Markevitch[b], Connor Martz[m], Hironori Matsumoto[f], Keiichi Matsuzaki[a], Dan McCammon[q], Brian McNamara[m], Joseph Miko[b], Eric Miller[af], Jon Miller[ag], Kenji Minesugi[a], Ikuyuki Mitsuishi[ab], Tsunefumi Mizuno[ah], Hideyuki Mori[b], Koji Mukai[b], Hiroshi Murakami[ai], Richard Mushotzky[ad], Hiroshi Nakajima[aj], Hideto Nakamura[a], Shinya Nakashima[x], Kazuhiro Nakazawa[ab], Chikara Natsukari[a], Kenichiro Nigo[ak], Yusuke Nishioka[j], Kumiko Nobukawa[al], Masayoshi Nobukawa[am], Hirofumi Noda[an], Hirokazu Odaka[n], Mina Ogawa[a], Takaya Ohashi[g], Masahiro Ohno[u], Masayuki Ohta[a], Takashi Okajima[b], Atsushi Okamoto[ak], Michitaka Onizuka[b], Naomi Ota[al], Masanobu Ozaki[a], Paul Plucinsky[o], F. Scott Porter[b], Katja Pottschmidt[b], Kosuke Sato[k], Rie Sato[a], Makoto Sawada[b], Hiromi Seta[g], Ken Shelton[b], Yasuko Shibano[b], Maki Shida[b], Megumi Shidatsu[l], Peter Shirron[b], Aurora Simionescu[a], Randall Smith[o], Kazunori Someya[ak], Yang Soong[b], Yasuharu Sugawara[a], Andy Szymkowiak[ao], Hiromitsu Takahashi[u], Toru Tamagawa[x], Takayuki Tamura[a], Takaaki Tanaka[ap], Yuichi Terashima[l], Yohko Tsuboi[aq], Masahiro Tsujimoto[a], Hiroshi Tsunemi[f], Takeshi Tsuru[ap], Hiroyuki Uchida[ap], Hideki Uchiyama[ar], Yoshihiro Ueda[t], Shinichiro Uno[as], Thomas Walsh[b], Shin Watanabe[a], Brian Williams[b], Rob Wolfs[d], Michael Wright[b], Shinya Yamada[g], Hiroya Yamaguchi[b], Kazutaka Yamaoka[ab], Noriko Yamasaki[a], Shigeo Yamauchi[al], Makoto Yamauchi[j], Keiichi Yanagase[ak], Tahir Yaqoob[b], Susumu Yasuda[ak], Nasa Yoshioka[ak], Jaime Zabala[b], Irina Zhuravleva[at], and *XARM* team

[a]Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Kanagawa 252-5210, Japan
[b]NASA/Goddard Space Flight Center, MD 20771, USA
[c]European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), 2200 AG Noordwijk, The Netherlands
[d]SRON Netherlands Institute for Space Research, Utrecht, The Netherlands

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[e]Faculty of Mathematics and Physics, Kanazawa University, Ishikawa 920-1192, Japan
[f]Department of Earth and Space Science, Osaka University, Osaka 560-0043, Japan
[g]Department of Physics, Tokyo Metropolitan University, Tokyo 192-0397, Japan
[h]Department of Astronomy, University of Geneva, Versoix CH-1290, Switzerland
[i]Department of Physics, Tokyo University of Science, Tokyo 162-8601, Japan
[j]Department of Applied Physics and Electronic Engineering, University of Miyazaki, Miyazaki 889-2192, Japan
[k]Department of Physics, Saitama University, Saitama 338-8570, Japan
[l]Department of Physics, Ehime University, Ehime 790-8577, Japan
[m]University of Waterloo, Ontario N2L 3G1, Canada
[n]Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
[o]Harvard-Smithsonian Center for Astrophysics, MA 02138, USA
[p]Lawrence Livermore National Laboratory, CA 94550, USA
[q]Department of Physics, University of Wisconsin, WI 53706, USA
[r]ALMA Regional Centre, ESO, D-85748, Garching bei Muenchen, Germany
[s]Department of Physics, Durham University, Durham DH1 3LE, UK
[t]Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan
[u]Department of Physical Science, Hiroshima University, Hiroshima 739-8526, Japan
[v]Department of Physics, Fujita Health University, Aichi 470-1192, Japan
[w]Department of Astronomy and Physics, Saint Mary's University, Nova Scotia B3H 3C3, Canada
[x]RIKEN Nishina Center, Saitama 351-0198, Japan
[y]Department of Physics, Tokyo University of Science, Chiba 278-8510, Japan
[z]Department of Physics, School of Science and Technology, Kwansei Gakuin University, 669-1337, Japan
[aa]Department of Physics, Rikkyo University, Tokyo 171-8501, Japan
[ab]Department of Physics, Nagoya University, Aichi 464-8602, Japan
[ac]Faculty of Science and Engineering, Waseda University, Shinjuku-ku, Tokyo 169-8555, Japan
[ad]Department of Astronomy, University of Maryland, MD 20742, USA
[ae]Department of Electronic Information Systems, Shibaura Institute of Technology, Saitama 337-8570, Japan
[af]Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, MA 02139, USA
[ag]Department of Astronomy, University of Michigan, MI 48109, USA
[ah]Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
[ai]Department of Information Science, Faculty of Liberal Arts, Tohoku Gakuin University, Miyagi 981-3193, Japan
[aj]College of Science and Engineering, Kanto Gakuin University, Kanagawa 236-8501, Japan
[ak]Tsukuba Space Center (TKSC), Japan Aerospace Exploration Agency (JAXA), Ibaraki 305-8505, Japan
[al]Department of Physics, Faculty of Science, Nara Women's University, Nara 630-8506, Japan
[am]Department of Teacher Training and School Education, Nara University of Education, Nara 630-8528, Japan
[an]Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Miyagi

980-8578, Japan
[ao]Yale Center for Astronomy and Astrophysics, Yale University, CT 06520-8121, USA
[ap]Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[aq]Department of Physics, Chuo University, Tokyo 112-8551, Japan
[ar]Science Education, Faculty of Education, Shizuoka University, Shizuoka 422-8529, Japan
[as]Faculty of Health Science, Nihon Fukushi University, Aichi 475-0012, Japan
[at]Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, CA 94305, USA
[au]Main Astronomical Observatory of National Academy of Science of Ukraine, 03143, Kyiv, Ukraine

ABSTRACT

The *ASTRO-H* mission was designed and developed through an international collaboration of JAXA, NASA, ESA, and the CSA. It was successfully launched on February 17, 2016, and then named *Hitomi*. During the in-orbit verification phase, the on-board observational instruments functioned as expected. The intricate coolant and refrigeration systems for soft X-ray spectrometer (SXS, a quantum micro-calorimeter) and soft X-ray imager (SXI, an X-ray CCD) also functioned as expected. However, on March 26, 2016, operations were prematurely terminated by a series of abnormal events and mishaps triggered by the attitude control system. These errors led to a fatal event: the loss of the solar panels on the *Hitomi* mission. The X-ray Astronomy Recovery Mission (or, *XARM*) is proposed to regain the key scientific advances anticipated by the international collaboration behind *Hitomi*. *XARM* will recover this science in the shortest time possible by focusing on one of the main science goals of *Hitomi*, "Resolving astrophysical problems by precise high-resolution X-ray spectroscopy".[1] This decision was reached after evaluating the performance of the instruments aboard *Hitomi* and the mission's initial scientific results, and considering the landscape of planned international X-ray astrophysics missions in 2020's and 2030's.

Hitomi opened the door to high-resolution spectroscopy in the X-ray universe. It revealed a number of discrepancies between new observational results and prior theoretical predictions. Yet, the resolution pioneered by *Hitomi* is also the key to answering these and other fundamental questions. The high spectral resolution realized by *XARM* will not offer mere *refinements*; rather, it will enable qualitative leaps in astrophysics and plasma physics. *XARM* has therefore been given a broad scientific charge: "Revealing material circulation and energy transfer in cosmic plasmas and elucidating evolution of cosmic structures and objects". To fulfill this charge, four categories of science objectives that were defined for *Hitomi* will also be pursued by *XARM*; these include (1) Structure formation of the Universe and evolution of clusters of galaxies; (2) Circulation history of baryonic matters in the Universe; (3) Transport and circulation of energy in the Universe; (4) New science with unprecedented high resolution X-ray spectroscopy. In order to achieve these scientific objectives, *XARM* will carry a 6×6 pixelized X-ray micro-calorimeter on the focal plane of an X-ray mirror assembly, and an aligned X-ray CCD camera covering the same energy band and a wider field of view. This paper introduces the science objectives, mission concept, and observing plan of *XARM*.

Keywords: X-ray, X-ray Astronomy, microcalorimeter, CCD

1. INTRODUCTION

As it inflated after the Big Bang, the Universe cooled to form particles and atoms. With further expansion and cooling, the particles and atoms eventually gathered and condensed to become galaxies and stars, and finally the large-scale structure that we see today. Throughout this cosmic expansion, dynamic flows of both matter and energy — from small to large-scale structures and vice versa — defined the evolution of its structure. Of course, the "feedback" mechanisms that drove this evolution are still at work in the present-day Universe.

For example, supernova explosions synthesize and distribute the heavy atomic elements formed inside their progenitor stars, and inject enormous quantities of energy into their local environments. The neutron stars and black holes left behind in supernovae can then accrete matter, efficiently converting kinetic energy to radiation. These processes heat the surrounding environment and accelerate particles to relativistic speeds. The highly energetic radiation and particles then permeate through the host galaxy and beyond, influencing its evolutionary path. Accretion onto massive black holes in galactic centers, potentially associated with galactic merger events, can *dominate* – not merely influence – the evolution of their host galaxy.

The evolution of galaxies in clusters can be even more complex. As these galaxies undergo their own dynamical and chemical evolution, they also move within the cluster, affecting their internal structure and formation through processes such as ram pressure stripping. The material that is stripped from these galaxies then mixes with the intracluster medium (ICM), enriches it with heavy elements and stirs gas motions in the ICM providing kinetic energy. Jets launched by black holes at the center of galaxy clusters can reshape the bulk of the baryonic matter within the cluster.

Clearly, cycles of matter and energy flux affect the evolution of structures in the Universe, on all scales. To elucidate the formation and evolution of the Universe, then, the mechanisms that drive these cycles must be understood and placed within the context of present-day structure. Much of the "feedback" that drives the evolution of structure can *only* be probed in X-rays, owing to the deep gravitational potentials, temperatures, and environments natural to highly energetic processes. Only with high-resolution X-ray spectroscopy we will be able to measure gas velocity shifts and gradients and study plasma properties in full details, revealing the *flows* of energy and mass in these settings.

A quantitatively and qualitatively new understanding of feedback awaits the era of high-resolution X-ray spectroscopy. *Hitomi* offered a glimpse of this era: the SXS micro-calorimeter[2] was the first instrument to achieve high-resolution spectroscopic measurements of spatially-extended high temperature plasmas.[3,4] This was achieved in the Perseus cluster of galaxies, the only deep exposure made using the SXS. However, the velocity resolution and imaging requirements are no less in other clusters, and no less in different environments. To examine the flows and cycles of matter on a galactic scale, for instance, a suitable X-ray instrument must have a velocity resolution of 100 km s^{-1} (or better) with sufficient spatial resolution. For these reasons, we define *XARM* science objectives 1 – 3 (Structure formation of the Universe and evolution of clusters of galaxies, Circulation history of baryonic matters in the Universe, and Transport and circulation of energy in the Universe) as described in section 2.

The initial results of *Hitomi* also revealed that real astrophysical plasmas are not completely described using our best current theoretical and laboratory-based predictions of the properties of heavy metal emission lines.[5–9] As *XARM* improves our understanding of, e.g., galaxy clusters and black hole feedback, our knowledge of astrophysical plasma line energy and intensity will also improve, enabling deeper and more precise insights into the physical settings being observed. Subtle but important processes such as charge exchange, and resonance and Compton scatterings in different plasmas, will be within the reach of the micro-calorimeter aboard *XARM*. Thus, the mission is expected not only to achieve leaps in our astrophysical understanding, but to test and improve our knowledge of fundamental atomic physics. Therefore *XARM* science objective 4 (New science with unprecedented high resolution X-ray spectroscopy) is also defined (section 2).

Hence, *XARM* will provide a multi-faceted tool for "Revealing material circulation and energy transfer in cosmic plasmas and elucidating evolution of cosmic structures and objects". A conceptual drawing of *XARM* satellite is shown in Figure 1. It will serve as a flagship mission to carry out astrophysics and to contribute to the wider field of physics in 2020's. The key scientific objectives for *XARM* are addressed in more detail in the following sections.

2. SCIENCE GOALS

2.1 Structure Formation of the Universe and Evolution of Clusters of Galaxies

Objects like galaxies and clusters of galaxies initially coalesce through the gravitational pull of dark matter, and they evolve into gigantic systems through collisions and mergers. How is the gravitational potential energy tapped by cluster mergers converted into thermal energy? How much of the energy is distributed into motion within the intra-cluster medium (ICM) and relativistic particles? To answer these questions, it is necessary to distinguish kinetic energy from thermal energy, and to evaluate how large the bulk and turbulent motions are. The evolution of the ICM also depends of the gas microphysics. The ICM is permeated by weak, tangled magnetic fields. Magnetic fields can be amplified by turbulent motions within the ICM, affecting the plasma

Figure 1. Conceptual drawing of *XARM* satellite. Two set of X-ray mirror assemblies are placed on the top plate, and detector instruments are installed on their focal plane inside the spacecraft.

thermal conductivity and viscosity. It is still difficult to evaluate these complex and coupled effects with numerical simulations, but observations can make the progress. For instance, measuring the level of turbulence on small spatial scales, one can put constraints on gas viscosity, enabling the studies of energy transport within clusters.

In the case of a cluster merger, it is predicted that the collision can be supersonic, with a mach number 2–3 or a speed of 2000 − 3000 km s^{-1}. Even in a large, relaxed cluster that is close to dynamical equilibrium, there can be small-scale non-uniformity in the observed surface brightness distribution.[10,11] If this non-uniformity originates in turbulent gas motions, it corresponds to a turbulent velocity of 300 − 400 km s^{-1}. The iron K-shell line complex at 6.7 keV (He-like iron) is the most prominent group of emission lines produced in the ICM. The thermal velocity of the ion is in the 10 − 100 km s^{-1} range. Therefore, to investigate the gas motions, it is important to measure the average velocity of this line complex and its dispersion to an accuracy of 100 − 200 km s^{-1}.

When a small galaxy group is accreted into a cluster, it causes magnetohydrodynamical interactions. Observations clearly determine that the distribution of galaxies in a cluster is more centrally concentrated than the distribution of ICM gas.[12] One theoretical model suggests that these in-falling galaxies heat up ICM.[13] This model can be tested by measuring the temperature and motion of gas stripped from the accreting galaxy group. For a typical gravitational potential in the central galaxy, and a reasonable sound speed, measurements that can address this theory must have an accuracy of gas velocity of 300 km s^{-1} or better.

The mass of galaxy clusters is dominated by dark matter, but it can be measured using the balance between the gradient of the gas pressure and the gravitational potential. However, non-thermal energy due to gas motions can skew such measurements. Ultimately, this can affect estimates of fundamental dark energy parameters that are derived using the cluster mass function,[14] making it essential to accurately measure the distribution of gas kinetic energy within clusters. Considering recently reported cosmological parameters and their uncertainty, the turbulent pressure must be measured to an accuracy of a few percent of the total pressure, which corresponds to a velocity dispersion of 200 km s^{-1}, if galaxy clusters are to contribute to our understanding of dark energy. It is crucial to measure the gas velocity fields in the outer region of the cluster, since gas in the core region is likely to be affected by feedback from the massive black hole in the central galaxy. The need to spatially separate the core and outer portions of clusters sets a requirement on the angular resolution of 1–2 arcminutes for nearby clusters.

The deep gravitational potential in the center of clusters will cause the densest, coldest gas to fall into the core. These "cooling flows" represent the translation of gravitational potential energy into kinetic energy and radiative energy. The coldest, densest gas radiates the most since the emissivity depends on $n^2T^{1/2}$, where n is the gas density and T is the gas temperature. Cooling flows are predicted to be efficient in some clusters or groups of galaxies, where the central region is so luminous in X-rays that temperature of ICM significantly drops and density rises unless there is a heating source.[15] However, the measurements with X-ray telescopes like *ASCA* revealed that the mass of the relatively cool gas in the central region is far less than expected in the cooling flow scenario.[13,16,17]

Where cooling flows are absent or moderate, some heating process must serve to limit or regulate the cooling. Several heating mechanisms are actively discussed in the field, including the interaction between the ICM and member galaxies,[13,18] thermal conduction from hot gas at large radii,[19,20] and the interation between jets launched by the central supermassive black hole and the ICM.[21–23] In the last scenario, the energy can be supplied to the gas through shocks and sound waves,[24] turbulence and g-waves produced during the buoyant rise of bubbles,[25,26] cosmic rays,[27,28] mixing of gas between ICM and the hot content of bubbles,[29] etc. Measuring gas motions in the central cool region and, more generally, detailed plasma properties through the high-resolution X-ray spectroscopy is a key for testing these heating sources.

Indeed, *Hitomi* observations of the Perseus cluster discovered that gas motions are subsonic with the velocity dispersion ∼100 – 200 km s^{-1} and the bulk velocity gradient ∼ 150 km s^{-1}.[3,4] Such velocities are roughly consistent with those triggered by the accretion of small clusters or by motions of the member galaxies,[13] by buoyantly-rising bubbles and g-modes[26] and by shocks and sound waves.[24,30] Additional observations along the radial directions as well as observations of clusters with different properties are required to achieve a clear understanding of the dominant feedback process in cluster cores. Observations with *XARM* will be able to determine the velocity structure of cluster gas with different temperatures, by utilizing the full pass band of its calorimeter to study K-shell lines from elements such as silicon and magnesium in addition to He-like iron.

2.2 Circulation History of Baryonic Matters in the Universe

Supernova remnants (SNRs) play an important role in the evolution of galaxies by injecting thermal and kinetic energy, heavy elements, and high-energy cosmic rays into the interstellar medium. Since the kinetic energy of the explosion is gradually thermalized in interacting with the interstellar medium and forming an optically thin plasma, plasma diagnosis with high-resolution X-ray spectroscopy is an ideal way to study how heavy elements are dispersed. *XARM* will measure the amount and the velocity of many elements ejected via supernovae (SNe). So far, only relatively abundant elements such as oxygen, iron, and silicon have been measured in detail with X-ray CCD spectrometers. In addition to these elements, *XARM* will measure the abundances of less abundant elements including chromium, manganese, and nickel. These abundances reveal the nucleosynthesis process in stars and how the products of nucleosynthesis are either ejected or collapse into degenerate stars. In addition, the timescale for these products to be integrated into the interstellar medium can be estimated by measuring the velocity of the explosion or turbulent motion. The X-ray micro-calorimeter on board *XARM* will cover the full range of expected ejection velocities, and thus it is an ideal instrument to directly observe the diffusion velocity of heavy elements into the interstellar medium. *XARM* will reveal not only the quantity of each heavy element or accelerated particle and the kinetic energy supplied to interstellar space by each SN, but also it will study their diversity by observing a large sample of objects. Many Galactic SNRs lie in the Galactic plane, where a number of bright X-ray binaries co-exist. Because the X-ray binaries may flare suddenly, simultaneous observation with a wide field X-ray imager is also required to evaluate the contribution of stray X-rays from time-variable compact sources to the X-ray micro-calorimeter, which has a small field of view.

SNe supply heavy elements not only to the interstellar medium in galaxies but also to the gas within clusters of galaxies, the ICM. Chemical abundances of heavy elements provide clues which can be used to identify the dominant SN explosion types and progenitor populations in cluster galaxies. For instance, oxygen, neon, aluminum, and magnesium are mostly synthesized in core-collapse (CC) SNe. In the synthesis of aluminum, particular elements like carbon and oxygen are needed, and thus abundance ratio between aluminum and magnesium reflects progenitor metallicity. On the other hand, the iron-group elements including iron, manganese, and nickel are mostly contributed by Type Ia SNe. The abundance of manganese in the ICM, in particular, is an indicator of a Type Ia contribution as CC SNe produces far less manganese. The relative abundance of elements traced by the nickel-to-iron abundance ratio can be used as a tracer of the principal origin of Type Ia

SNe, i.e., accretion from a companion star to a white dwarf, merger of white dwarf binary, or both. Although the chemical abundances of heavy elements carry important information, spectroscopy with X-ray CCDs is limited by the energy resolution: emission lines from neon, magnesium, aluminum, and nickel are not completely resolved due to contamination from prominent iron lines.[31] Also, emission lines from less abundant elements such as aluminum, chromium, and manganese are usually too faint to detect with X-ray CCDs. *XARM* will measure these spectral features precisely for the first time by minimizing systematic uncertainty with the capabilities of the X-ray micro-calorimeter.

2.3 Transport and Circulation of Energy in the Universe

One of the most important challenges for understanding of the evolution of cosmic structure is to reveal how galaxies and super-massive black holes (SMBHs) in galactic centers evolved together. This requires explanation owing to the fact that the masses of the central black holes in galaxies are correlated with the mass and velocity dispersion of the stars in the galaxy central region. In addition, an even more fundamental problem, the mechanism of feeding mass onto SMBHs from the host galaxies, is poorly understood. Many observations suggest that the SMBH in an active galactic nuclei (AGN) is surrounded by a "torus" composed of gas and dust. It is believed that the torus is a reservoir of matter supplied from the galaxy. However, we know little about the basic properties of AGN tori such as the geometry, mass distribution, and velocity field, which carry critical information on the SMBH mass feeding process. X-ray observations are an crucial technique to reveal the distribution of all matter (both gas and dust) around a SMBH. The torus absorbs and scatters the X-ray continuum emission from the nucleus, producing a reflection component which is accompanied by a narrow iron-K fluorescence line. Since matter in the torus orbits the SMBH according to Kepler's law, a measurement of the Doppler-width of the narrow line leads to constraints on the distance of the torus from the SMBH, normalized by the black hole mass. Assuming a black hole mass of $10^8 M_\odot$ and a typical torus location of $1-10$ pc, the velocity width is estimated to be $200-700$ km s^{-1}. Recent theoretical studies predict possible additional turbulent motions produced by SNe inside the torus. Furthermore, we expect that the narrow line from the torus will also contain contributions from the broad line regions. Thus, the observed line profile is expected to be complex. In order to precisely measure the width of the torus-originated narrow line by separating it from other broader components, *XARM* is required to have a capability of measuring the iron-K line width with an accuracy of 200 km s^{-1}.

The feedback from SMBHs to the intergalactic medium is believed to be mainly driven by AGN outflows. An outflow from the accretion disk around a black hole (disk wind) can inject a large amount of kinetic energy into the surrounding interstellar medium. The surrounding matter is then pushed outward and consequently both star forming activity and mass accretion onto the SMBH are inhibited. The disk wind is a photo-ionized plasma irradiated by the intense radiation from the central disk and is often composed of highly ionized ions such as He-like and H-like iron. Observations suggest a trend that a more highly ionized wind has a higher outflow velocity. Hence, in order to understand the overall picture of outflows, it is crucial to trace fast and highly ionized gas through X-ray spectroscopy.[32,33] When such a disk wind intersects the line-of-sight of an observer, absorption lines appear in the X-ray spectrum. The most important quantity to evaluate the significance of AGN feedback is the wind power, which is estimated from the outflow velocity, density, location, and solid angle of the wind. High resolution spectroscopy with *XARM* will enable us to directly measure the detailed absorption line profiles of highly ionized ions, not only the outflow velocity but also the velocity dispersion. It is known from previous observations that outflow velocities and velocity dispersions of ionized absorbers in AGNs are typically $100-1000$ km s^{-1} and < 500 km s^{-1}, respectively. Therefore, *XARM* is required to have a capability to determine a line energy with an accuracy of < 100 km s^{-1}. Furthermore, in order to spectroscopically resolve the velocity dispersion, *XARM* will have a capability of determining a line width with an accuracy of < 200 km s^{-1}.

Disk winds are a common phenomenon in accreting compact objects; highly ionized winds with outflow velocities of $300-3000$ km s^{-1} are often observed in X-ray binaries containing a stellar-mass black hole or a neutron star. These Galactic compact objects are brighter than AGNs in the X-ray band by $1-2$ orders of magnitude, thus providing ideal laboratories to study detailed spectral structures produced by the disk winds. The mass of a stellar-mass black hole is ~ 6 orders of magnitude smaller than that of the SMBH in an AGN. Hence, comparison of the disk-wind properties with stellar-mass and SMBHs, enable us to globally understand the physics of disk winds that depend on the black hole mass or mass accretion rate, including their driving mechanisms (thermally, radiatively, and/or magnetically driven winds). In order to perform this study, the high resolution spectrometer must be able to observe very bright sources efficiently.

2.4 New Science with Unprecedented High Resolution X-ray Spectroscopy

The capabilities of *XARM* will open a wide range of new science beyond those scientific objectives described above. Prior to 2000, X-ray observatories had been inferior to optical band instruments in spatial- and energy resolution. However, in 1999 the advent of *Chandra X-ray Observatory* provided spatial resolution below 1 arcsecond, and then in 2016 *Hitomi* succeeded in providing energy resolution $E/\Delta E \sim 1200$ at the iron K- line energy. These X-ray observatories show how new technology can reveal completely new aspects of the universe.

High resolution spectroscopy extracts information about the physical state of plasmas and leads to understanding the physical properties of X-ray objects. For example, plasma diagnosis of spectral structures enabled by *XARM* will tell us how these plasmas have been formed. Recent studies indicate that the SNR plasmas have evolved through more complicated processes than what have been thought previously. Namely, in some SNRs, electron temperatures are higher than ionization temperatures, and recombining plasmas are present.[34] This suggests that such plasmas have experienced rapid cooling, rather than monotonically evolving in a uniform medium. Since there are molecular clouds and their cavities ubiquitously distributed in interstellar space, the study of the evolution of such plasmas by looking into their transient states is necessary for the understanding of SNR plasmas in real systems.

XARM will observe various SNR plasmas in transient states, determine the origin of plasmas, and will improve understanding of the process of enrichment by heavy elements. High-resolution spectroscopy will resolve emission line complexes from silicon, sulphur, and iron, which have been seen as one line with CCD instruments, into many lines and will detect weak lines. Ratios of the emission line intensities will show us temperature structure and non-equilibrium characteristics and will enable us to confirm new plasma processes such as charge exchange and resonance scattering. Among the Heα emission lines, one important measurement is the ratio of the resonance line (w) and forbidden line (z). This ratio indicates the conditions in the radiating source: whether it is in collisional ionization equilibrium, in ionization non-equilibrium, under a charge exchange process, or in a photo-ionization-dominated state. Furthermore, the emission of hot plasmas produces many satellite lines, whose intensities reflect the fraction of non-thermal electrons and their ratios are determined by various physical conditions including the electron temperature. The high-resolution spectroscopy opened by *XARM* is expected to bring about many new science results, such as measurement of low energy cosmic rays, using neutral iron lines produced by collisional ionization, and indirect study of the plasma velocity field in clusters of galaxies using resonance scattering effects. These new observational features will expand a new area of astrophysics as we proceed the X-ray observations mentioned before.

The X-ray micro-calorimeter combines high resolution spectroscopy with accurate timing and with a high level of accuracy. This makes new observations possible that could not be done with past dispersive spectrometers. For example, in observational studies of relativistic objects, X-ray spectra obtained with high resolution X-ray spectroscopy can probe strong gravitational field of white dwarfs, neutron stars and black holes. *ASCA* observations discovered relativistically red-shifted iron fluorescent emission line, produced in the close vicinity of black holes. There were many follow-up observations carried out, but detailed studies of this feature are challenging. This is because the X-ray spectrum in this energy range contains several additional reflection and absorption features. *XARM* will provide wide-band and high-resolution spectrum at energies extending well above the iron fluorescence line, enabling us to separate and study the fluorescence line with the best accuracy so far. With *XARM*, we expect to more clearly measure and identify gravitational redshift and time variation arising from motions of the accretion disk.

Lastly, we add that the capabilities of *XARM*, as defined by the mission requirements, will open a wide range of new science including searches of missing baryons and decay lines from dark matter particles.

2.5 Summary of Scientific Objectives

Hitomi opened the door to high resolution X-ray spectroscopy with its groundbreaking observation of the Perseus cluster of galaxies. Revealing for the first time the dynamics and detailed chemical composition of a cluster atmosphere, it is clear that *Hitomi* only scratched the surface of rich physics high resolution X-ray spectroscopy will explore. *XARM* will enable a qualitative leap in our understanding of the origin and circulation matter and energy in the universe.

XARM's primary scientific objectives include:

(SO-1) In order to investigate Structure formation of the Universe and evolution of clusters of galaxies, *XARM* shall reveal spatial distribution and their dissipation of thermal and non-thermal energy of the largest gravitationally bounded system — clusters of galaxies, and directly observe sites of their growth mechanism from both thermo-dynamic and kinematic aspects.

(SO-2) In order to investigate Circulation history of baryonic matters in the Universe, *XARM* shall trace baryon cycles in various stages from element synthesis by stellar objects and supernovae to material dissipation in interstellar to intergalactic space, and directly observe the element abundance evolution in the cosmic structure formation.

(SO-3) In order to investigate Transport and circulation of energy in the Universe, *XARM* shall reveal matter and energy feedback by galaxies and active galaxies, and observe its impact to the co-evolution of galaxies and supper-massive black holes.

(SO-4) In order to realize New science with unprecedented high resolution X-ray spectroscopy, *XARM* shall develop new methods of plasma diagnostics, and measurements of velocity and gravitational redshift shown in spectra of materials around relativistic objects to pioneer new horizon of X-ray astrophysics.

XARM achieves the scientific objects described above by "Pioneering new horizon of the Universe with unprecedented high resolution X-ray spectroscopy".

3. MISSION REQUIREMENTS AND OBSERVATION PHASES

3.1 Mission Requirement

Here we describe mission requirements to realize scientific objectives listed above.

(MR-1) In order to realize SO-1, *XARM* shall observe ICM of nearby ($z < 0.1$) clusters of galaxies resolving core region from the outer region in the accuracy of 100 kpc, to reveal distribution of both thermal energy and velocity distribution of the ICM by the imaging and precise spectroscopy. The non-thermal energy of bulk motion and turbulent motion of ICM shall be measured within the accuracy of that of thermal energy. In number, using the iron-K lines (about 6 keV) measure the line of sight average velocity and velocity dispersion with the accuracy of less than 100 and 150 km s^{-1} (1σ), respectively.

(MR-2) In order to realize SO-2, *XARM* shall directory observe nucleosynthesis and ejection of elements around stars and SNRs. *XARM* shall determine abundance (of nitrogen, oxygen to iron or nickel) and dissipation velocity of the various stages with the best accuracy so far realized. Also search for rare elements, such as aluminum, chromium and manganese with the best ever accuracy. Especially utilizing the iron emission line, *XARM* shall determine the line of sight expanding velocity in the accuracy of less than 100 km s^{-1}. The amount of photon contamination from the transient source out of the field of view of the high-resolution spectrometer shall be well evaluated.

(MR-3) In order to realize SO-3, *XARM* shall resolve the iron emission line profile in the reflection component from AGN torus, to determine the basic property of the torus, including geometry, mass distribution, and velocity field. For this purpose, *XARM* shall determine the line of sight velocity and the velocity dispersion of iron emission line in the accuracy of less than 200 km s^{-1}.

(MR-4) In order to realize SO-3, *XARM* shall observe hot galaxy wind and accretion disk wind of AGNs to determine the density and velocity. The required accuracy of the line of sight velocity and velocity dispersion shall be less than 100 and 150 km s^{-1}, respectively. The continuum of AGN emission shall be observed in the energy range up to 13 keV to well resolve the highly ionized plasma effects from thermal plasma or reflection components.

(MR-5) In order to realize SO-4, and to provide capability as "general purpose X-ray observatory of 2020s", *XARM* shall possess capability to observe 100 typical targets per year.

3.2 Science Instrument Requirements

XARM carries two science instruments: the *Resolve* Soft X-ray Spectrometer and the *Xtend* Soft X-ray Imager. Two identical X-ray Mirror Assemblies (XMAs) are mounted on the top plate of the spacecraft focusing X-rays onto the two science instruments located on the base plate of the spacecraft. Resolve is equipped with a microcalorimeter spectrometer array which will deliver 7 eV energy resolution or better. Xtend consists of the XMA and the wide field X-ray CCD camera, delivering moderate energy resolution.

Imaging capability The XMA optics will deliver ≤ 1.7 arcmin in Half Power Diameter (HPD) point spread function. Resolve's 30 arcsec pixels will oversample the PSF and provide a 3 arcmin square field of view. Xtend will likewise oversample the core of the point spread function. Comparing these characteristics to prime cluster target Abell 478 at redshift $z = 0.09$, an angular size of 1.7 arcminutes corresponds to a linear size of roughly 200 kpc, somewhat larger than its atmospheric core radius.

Among the primary targets for SO-1, discussed in *ASTRO-H* White Paper, is Abell 2029 lying at redshift $z = 0.077$. The *XARM* observation shall resolve the atmospheric turbulence near r_{2500}[*] (660 kpc in Abell 2029), while avoiding scattered light from the bright central region using a typical exposure time of of 100 ks (MR-5). This will require an effective area of around 200 cm^2 at 6 keV and field of view of around 3×3 arcmin. Xtend will determine the continuum spectral components of targets, identify, and characterize targets located just outsize of Resolve's field of view. Xtend observations will be used to mitigate scattered light into Resolve's field of view. Thus Xtend's field of view is larger than Resolve's. Xtend's field of view (FOV) must exceed a few HPDs outside the Resolve FOV, which corresponds to $\sim$ 15 arcmin. This figure reflects the fact the X-ray mirror optics of *Hitomi* had a 1/1000 leakage of photons out at 15 arcmin. Thus, if a 1 Crab source is located 15 arcmin. away, it will provide photon flux of 100 μCrab in the center. This number is 1/10 of the typical target flux of 1 mCrab source, and thus can be sufficiently modeled for most Resolve applications.

Spectroscopy capability From the requirements MR-2 (low energies) and MR-4 (high energies), Resolve shall measure X-rays across the energy range $0.3 - 13$ keV. This energy range covers emission lines from nitrogen (0.4 keV) to highly ionized iron lines ($6 - 8$ keV) and its absorption edge (spectral structure above $\sim$ 9 keV) from objects lying below redshift $z < 0.1$. While the high resolution spectrometer will observe the nitrogen line at 0.4 keV, the nitrogen line is relatively weak and is thus difficult to identify with the moderate spectral resolution. Nevertheless, moderate spectral resolution across a wide band is crucial for broad-band continuum characterization. Therefore, Xtend is required to cover oxygen line at 0.5 keV and the iron line and edge structure at 9 keV and above.

The requirements MR-1 and MR-4 set Resolve's the energy resolution. For nearby objects lying below redshifts $z < 0.1$, a velocity dispersion of 150 km s^{-1} corresponds 3 eV at 1 sigma for a single spectral line. The high resolution spectrometer shall determine the line width similar or better than 7 eV FWHM (equivalent to 3 eV at 1 sigma).

MR-2 and MR-4 requires an accurate absolute energy scale calibration. A doppler shift of 100 km s^{-1} corresponds to a 2 eV shift in energy at iron for objects with redshifts below $z < 0.1$. Therefore, Resolve shall determine the central energy of strong emission lines to similar accuracy. In addition, Xtend must resolve contaminating emission from background and foreground sources. It shall be capable of resolving the He-like iron emission lines and the H-like iron emission lines in order to characterize extended radiation around the field of view of the high resolution spectrometer.

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[*] The radius within which the mass density of a cluster is equal to 2500 times the critical density of the Universe

Capability as an observatory Consistent with *Hitomi's* science case, *XARM* shall observe sources with fluxes of 1 mCrab flux or below. Its effective area requires that for a typical exposure time of 100 ks (MR-5) roughly 30 photons would be detected within a 7 eV range (derived from energy resolution FWHM). The background count rate shall lie below ≤ 1 count (100 ks exposure)$^{-1}$ (7 eV)$^{-1}$ $\sim 2 \times 10^{-3}$ counts s^{-1} keV^{-1} per array.

The *Hitomi* science case analysis indicates that *XARM* shall observe sources as bright as 100 mCrab. Its effective area will yield 150 counts s^{-1} per array for a 100 mCrab source. Resolve shall be capable of detecting this flux, providing spectroscopy with unprecedented resolution.

Observatory characteristics are summarized in Table. 1.

Table 1. Key parameters and performance requirement of the payload

Parameter	Resolve	Xtend
X-ray mirrors	conically approximated Wolter I optics (203 nested shells)	
Focul length	5.6 m	
Angular resolution	≤ 1.7 arcmin (HPD)	
Detector technology	X-ray micro-calorimeter	X-ray CCD
Effective area	≥ 210 cm^2 @ 6 keV, ≥ 160 cm^2 @ 1 keV	≥ 300 cm^2 @ 6 keV
Feild of View	2.9×2.9 arcmin^2.	$\geq 30 \times 30$ arcmin^2
Energy range	$0.3 - 12$ keV	$0.4 - 13$ keV
Absolute energy scale	≤ 2 eV	—
Energy resolution	≤ 7 eV FWHM @ 6 keV	≤ 250 eV @ 6 keV (EOL)
Non X-ray background	$\leq 2 \times 10^{-3}$ c/s/keV/array	$\leq 1 \times 10^{-6}$ c/s/keV/arcmin^2/cm^2 (in $5 - 10$ keV)
Time tagging accuracy	≤ 1 ms	—

The science objectives and mission requirements described here are consistent with those for the instruments in common with *Hitomi*. For example, *XARM*'s Resolve and Xtend instruments are nearly identical to the *Hitomi* SXS and SXI. The enormous lost potential of *Hitomi* and the high impact of its early results made a compelling case for JAXA, NASA, and ESA to embark on *XARM*. Detailed description of the Resolve and Xtend imagers are presented in separate papers.

3.3 Observation Phases

XARM is planned to be operated in three phases, the first commencing immediately following the post-launch checkout and calibration period.

Phase 1 will be six months in duration and will be allocated to observing targets defined by the *XARM* Science Team. During this period, partner countries may release an Announcement of Opportunity (AO) to engage the broader scientific community to participate in the analysis of Phase 1 data.

Phase 2 will be 12 months in duration. During Phase 2, observing time will be primarily allocated to Guest Observers through the AO processes open to the scientific communities of participating countries. Some Phase 2 time may be allocated to the observatory and *XARM* Science Team targets that were not observed during Phase 1.

Phase 3 will commence immediately following Phase 2 and will continue until mission completion. During Phase 3, all available observing time, apart from time reserved for the observatory and key projects, will be allocated to Guest Observers through the AO process. The nominal mission life is three years, which corresponds to the expected life of the liquid helium cryogen for Resolve. Observation is expected to continue beyond three years using the mechanical cooling system.

The scientific data yielded by *XARM* shall be made available to the scientific community following a short proprietary period.

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