Search for WHIM with Suzaku and Future Prospects

T. Ohashi[1], H. Akamatsu[1], I. Mitsuishi[2], Y. Takei[2], N. Y. Yamasaki[2], K. Sato[3], and M. Galeazzi[4]

[1] Department of Physics, Tokyo Metropolitan University
[2] Instisute of Space and Astronautical Science, Japan Aerospace Exploration Agency
[3] Graduate School of Natural Science and Technology, Kanazawa University
[4] Department of Physics, University of Miami
E-mail(TO): ohashi@phys.metro-u.ac.jp

Abstract

Status about the Suzaku search of warm-hot intergalactic medium (WHIM) is briefly reported. Astrophysical importance of this study is described. Good energy resolution in the soft X-ray energy range and low background of XIS give us the highest sensitivity so far for WHIM. Cluster outskirts of A2142 and Shapley supercluster regions are discussed in some detail. We obtained the typical upper limit for the gas density to be about $300(L/2\mathrm{Mpc})^{-1/2}(Z/0.1Z_\odot)^{-1/2}$, with L and Z the line-of-sight depth and the metallicity of the WHIM cloud. Future dedicated missions for the WHIM search, DIOS and Xenia, are briefly described.

Key words: intergalactic medium — galaxies: clusters — cosmology: observations

1. Introduction

Baryons consitute only about 4% of the total energy density in the present universe. Even for those baryons, less than half of them has been identified as hot and cold gas and stars (Fukugita et al. 1998), and the rest is predicted to be in the form of warm-hot intergalactic medium (WHIM) with temperatures 10^{5-7} K (e.g. Cen & Ostriker 1999). Figure 1 shows the baryon distribution in the density-temperature space in the local universe taken from Branchini et al. (2009). The central region in this diagram, with overdenstiy 1–1000 and temerature 10^{5-7} K, corresponds to WHIM. Many small circles overlaid in this plot show expected sensitivity of dedicated X-ray missions. Clearly, WHIM forms a major part of the whole baryons and it needs to be stuied for our deeper understanding of the structure formation and chemical enrichment of the universe.

Because WHIM escapes from our detection, it is also called as missing baryons. Since the density of WHIM is only 10–100 times the average level in the local universe, their detection has not been successful. There have been reports of WHIM detection based on both absorption line and continuum emission measurements, however we need independent high quality confirmations to establish those detections (Nicastro et al. 2005; Kaastra et al. 2006; Rasmussen et al. 2007). Additional difficulty for the WHIM search is that the temperature is close to the foreground Galactic emission (see Yamasaki 2009), and the separation is only possible with the redshift of emission or absorption lines. Therefore, high-resolution spectroscopy is really needed to make a substantial progress in the WHIM study.

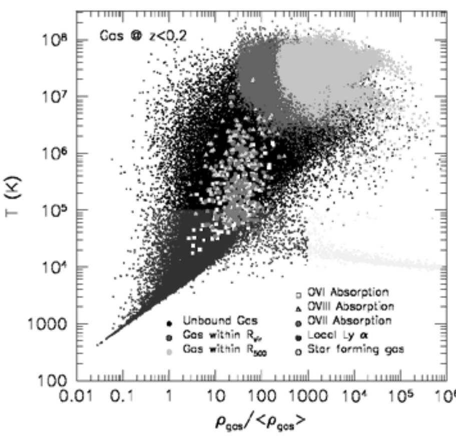

Fig. 1. Phase space diagram of the baryons at $z < 0.2$ taken from Branchini et al. (2009) which is based on numerical simulation by Borgani et al. (2004).

WHIM is expected to carry very rich information about the thermal and chemical history of the universe. As a result of the first star formation, the intergalactic space was reionized at $z \approx 11$ (Dunkley et al. 2009). Then, as the galaxies are formed, the surrounding space has been enriched with metals. The formation of the large-scale structure caused the WHIM contained in the filaments to be heated up. Therefore, WHIM was created as a natural reaction of galaxy and structure formations. Study of WHIM will give us an opportunity to look at the evolution of the universe from a different viewing angle, compared with the traditional observations of stars and galaxies.

2. Recent Suzaku studies

We will report on recent 2 observational studies from Szaku. One is the outer region of a merger cluster A2142 ($z = 0.0909$) and the other is the Shapley supercluster ($z = 0.048$). Since Shapley observations are separately reported by Mitsuishi et al. (2009) in this volume, we will be very brief about it.

2.1. A2142

A2142 is a very hot ($kT \approx 9$ keV) and luminous cluster, from which the first evidence of cold fronts has been reported by Markevitch et al. (2000). The cluster looks slightly elongated in the direction of merger axis (from northwest to southeast). These features suggest that there may well be a large-scale filament running in this direction, since a subcluster infall has already occurred in the past. The other feature of A2142 is its right redshift at $z = 0.0909$. With redshift approaching 0.2, OVIII line from WHIM tends to overlap with the Galactic OVII line and the shifted OVII line also overlaps with a spectral hump produced by oxgen edge due to XIS filters.

Observations of 3 regions offset from A2142 were carried out in August-September 2007, with the XIS instrument, as shown in figure 2. The field centers are $16'$, $25'$ and $41'$ (r_{180} corresponds to $26'$) offset from the cluster center, which we thought were most effective to search for the WHIM emission. Therefore, the Suzaku observations have covered almost to $2r_{180}$.

In order to search for WHIM using both redshifted O lines and excess continuum spectrum, we need background spectrum taken in near-by regions. For this purpose, we looked at the third pointing data, which is the farthest from A2142, and a data pointed at T CBr located at about 5° from the cluster. These spectra agree well with each other, and are consistently fitted with standard Galactic emission. The Galactic emission consists of the Local Hot Bubble ($kT \sim 0.1$ keV) and Milky-Way Halo (0.3 keV). Using this 3rd pointing data as the background, cluster temperature was traced to about 1.2 r_{180} with $kT = 2.1^{+3.4}_{-1.5}$ keV at $0.95 - 1.2$ r_{180} and 1.1 ± 0.4 keV at $1.2 - 1.5$ r_{180}, respectively. Systematic errors due to uncertainty in the XIS filter contamination and fluctuation of cosmic X-ray background give additional error in temperature by 1–2 keV. Therefore, A2142 shows a dramatic temperature drop from 9 keV to nearly 1 keV, and we will look into the question of how such a temperature drop can be explained in the theoretical framework.

We also searched for spectral signatures of redshifted OVII and OVIII emission lines, finding no significant evidence. The data we fitted were for the region $1.2 - 1.5$ r_{180} from the cluster center. The 2σ upper limits fo line intensities are $< 2.3\times10^{-7}$ and $< 2.1\times10^{-7}$ photons cm^{-2} s^{-1} arcmin^{-2} for OVII and OVIII lines, respectively, as shown in figure 3. Assuming the line-of-sight depth for the possible WHIM clound to be 2 Mpc with the metal abundance of 0.1 solar, the inferred upper limit for the gas overdensity δ (ratio to the average baryon density in the local universe, $1.77\times10^{-7}(1+z)^{-3}$ cm^{-3}) becomes 560 for both lines. This value is rather high compared with the previous report for A2218 ($\delta < 270$) based on Suzaku observations with the same assumption about the WHIM size and metallicity (Takei et al. 2007).

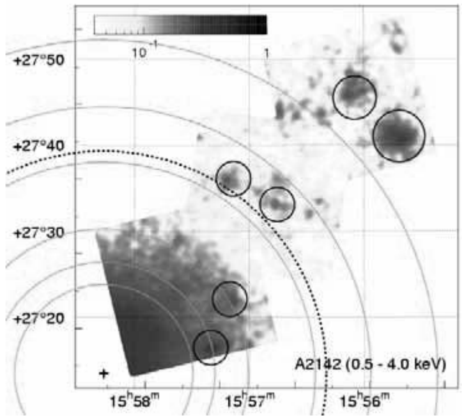

Fig. 2. Suzaku image for A2142 cluster taken near the virial radius, shown as a dotted circle. Other large circles show radial regions for spectral analysis. Six sources removed are shown with solid circles.

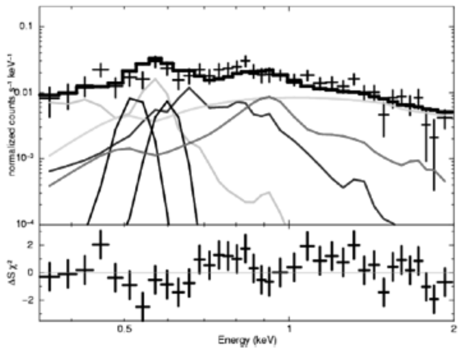

Fig. 3. Upper limits for redshifed OVII and OVIII lines fitted to spectra for the region $1.2 - 1.5r_{180}$ from A2142.

2.2. Shapley supercluster

This supercluster has a redshift $z = 0.048$ characterized by the brightest central cluster A3558. Suzaku performed 3 pointings, with the one between A3558 and A3556 (separation is 1 r_{180} from both clusters), 1° offset in the north direction, and $\sim 4°$ offset in the north-east direction. The first region showed a significant excess in the ROSAT data (Kull & Böhringer 1999). The last pointing gives a spectrum consistent with the standard Galactic background and was used as the background for the other 2 pointins. As described by Mitsuishi et al. (2009) in this volume, we found an excess emission around 1 keV for both the data. Since the redshift is small, the excess component can be fit by both the Galactic and Shapley emissions, with $kT \approx 0.8$ keV in the latter case. If we assume that the emission is associated with the supercluster, then the inferred gas overdensity becomes $255(L/4\mathrm{Mpc})^{-1/2}$ which is a fairly low upper limit even though the assumed line-of-sight depth L is somewhat large.

The no detection of redshifted OVII and OVIII lines sets an upper limit for the WHIM overdensity. Assuming the same depth and oxygen abundance of 0.1 solar, the OVIII line gave a low limit of $\delta < 204(L/4\mathrm{Mpc})^{-1/2}$. Since the redshifted OVIII line falls close to the spectral valley between the OVII and OVIII lines, the data gave a very low upper limit for the line intensity.

Even though the data do not allow us a definite conclusion, the presence of the possible 0.8 keV emission only around the supercluster region is suggestive. The temperature is too high even considering the spatial fluctuation of the Galactic emission, and rather close to the bottom value of the temperature decline in the cluster outskirts. The spectrum is very different from those due to the solar wind effect. We need to look at other Suzaku data for superclusters and cluster outskirts if similar soft emission may be seen in those unvirialized regions.

3. Summary of Suzaku observations

Suzaku has carried out WHIM search for several clusters of galaxies. Regarding the search of redshifted OVII and OVIII emission lines in cluster outskirts, all the observations give upper limits, which are summarized in figure 4. The A1413 data were taken from Hoshino et al. (2009) in this volume, and the Coma-11 results are given by Takei et al. (2008). Measured intensity for the typical Galactic lines by McCammon et al. (2002) are also shown for comparison. These upper limits correspond to overdensity of the WHIM to be $\delta \sim 300$. This overdensity is larger than those near r_{180} of clusters, where X-ray emission is barely detectable with Suzaku. This is because constraint set by only the oxygen lines is weaker than those using the whole spectrum.

Although there may be X-ray emission produced by WHIM with $kT \sim 0.8$ keV or lower, the definite evidence will be only obtained through the detection of redshifted lines. If energy resolution becomes 10 times better than the XIS level, the S/N ratio becomes better by a factor of 3.2 if the same effective area and the same solid angle are given. This may give a reduction of detectable overdensity by a factor of 1.8 ($= \sqrt{3.2}$) since the intensity scales as density squared. However, with 10 times better energy resolution, we will be able to find good energy ranges (or target redshift) so that there are no Galactic emission lines overlapping with redshifted O lines. So, S/N ratio would become even higher than this, and we expect a substantial improvement in the WHIM study.

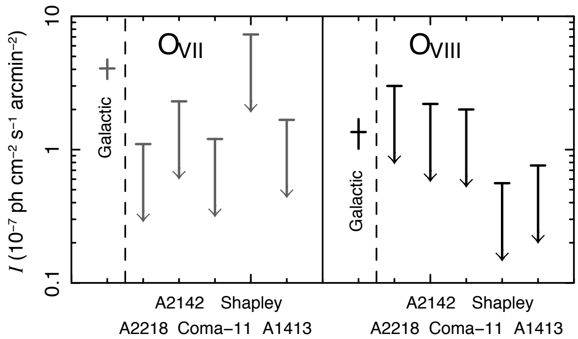

Fig. 4. 2σ upper limits for the OVII and OVIII line intensities measured with Suzaku in cluster outskirts compared with Galactic line intensities by McCammon et al. (2002).

We will continue our effort of the WHIM search using Suzaku and other X-ray observatories, however it looks likely that the firm X-ray evidence of WHIM will have to wait for the advent of microcalorimeters.

4. Future prospects

It is getting quite clear that a substantial improvement in energy resolution is necessary for the unambiguous detection of WHIM. Therefore, this is an area where microcalorimeters will give substantial improvement, and several dedicated X-ray missions have been proposed.

The first mission we introduce is a mission under the Japanese small scientific satellite program called as DIOS (Diffuse Intergalactic Oxygen Surveyor: figure 5). Details about the spacecraft and status of technology development can be found in Ohashi et al. (2006) and in Tawara et al. (2008). The purpose of DIOS is to carry out survey observations of WHIM using redshifted OVII and OVIII emission lines. For this purpose, DIOS will employ an array of TES microcalorimeters cooled by mechanical coolers and combined with a 4 reflection X-ray telescope. Previous observations with CCD detectors have difficulties in detectecting and separating redshifted emission lines from the Galactic emission unambiguoudly. Even grating spectrometers on-board Chandra and XMM-Newton give controvertial results about the absorption lines attributed to WHIM against bright emission from a blazar Mkn 421. The superior energy resolution ($\Delta E \approx 2$ eV) with TES and wide grasp ($S\Omega$) by the telescope will bring orders of magnitude advance in the sensitivity for the WHIM detection.

The DIOS satellite will weigh about 400 kg, and will carry one X-ray telescope whose outer shells consist of

4 reflection stages and an array of TES microcalorimeters having 256 pixels. The 4 reflection telescope has a focal length of only 70 cm, enabling the focal plane detector of 1 cm square to cover a sky area of $50' \times 50'$. The covered energy range will be limited to 0.3–2.0 keV where 4 reflections do not degrade the effective area by 60% from the 2-reflection level. The TES instrument will be cooled to $\leq$ 100 mK by a combination of mechanical coolers and adiabatic demagnetization refrigerators, giving an unlimited life of operation.

The instrument will give $S\Omega \geq 100$ cm^{2}deg^2, which gives the sensitivity to extended sources even higher than the planned large X-ray observatories. Since a pointing of 1 Msec will be necessary to detect WHIM, a toal area of a few square degrees will be mapped in 2 years. The short focal length will also give an extremely low background, since a sky region will be observed by a very small detector area. Besides the study of WHIM, DIOS will give us unprecedented sensitivity for cluster outskirts, supernova remnants, Galactic hot gas, and geocoronal charge exchange emission.

DIOS is planned to be implemented after ASTRO-H, whose launch is scheduled to be in February 2014. So, the likely launch year will be around 2016. The formal mission proposal will be submitted within the next few years to meet the selection process of future small scientific satellites.

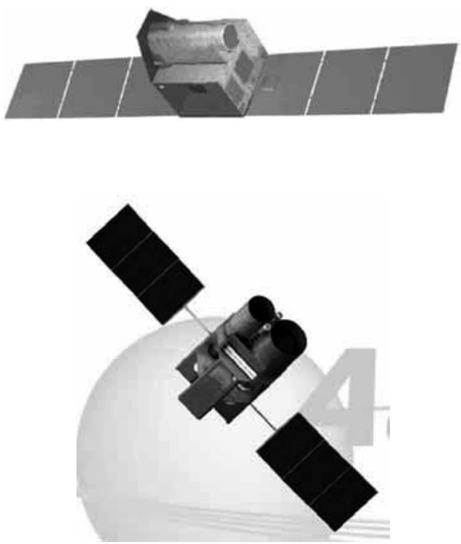

Fig. 5. Proposed X-ray missions to explore WHIM using high-resolution spectroscopy: DIOS (top) and Xenia (bottom)

A scaled-up version of DIOS has been discussed and was proposed to ESA's cosmic vision (as EDGE) and to US Decadal Survey (as Xenia[1] shown in figure 5). The satellite will weigh about 2000 kg and will carry CCD instruments and gamma-ray burst detectors along with wide-field TES calorimeters. The major improvements for Xenia/EDGE are larger $S\Omega$ of about 600 cm^{2}deg^2, fast slewing capability, and wide field CCD camera.

Apart from the large grasp of the TES calorimter instrument, the fast slewing capability enables Xenia to observed absorption features due to WHIM against X-ray afterglows of γ-ray bursts. Since γ-ray bursts are produced by distant galaxies up to $z = 8$, and extremely bright in X-rays if they can be observed within 1 min of the burst onset. The fast slew function is successfully working in SWIFT satellite, so it is a reliable technology. Therefore, absorption lines and edges by intervening WHIM as well as by host galaxies of the bursts can be observed with TES calorimeters. The absorption line observations against γ-ray bursts enable probing of WHIM clouds in high-redshift universe for the first time. Also, the WHIM cloud which produced absorption lines can be observed with emission lines when afterglows faded out. Based on the simultaneous knowledge for both emission and absorption for the same cloud, we can solve for the density and line-of-sight depth of the cloud. This provides a unique method to estimate the geometry and physicsl state of WHIM, giving a strong constraint to theoretical models.

Among the many subjects where high resolution spectroscopy will bring substantial advances in science, the WHIM study will see a real breakthrough with future dedicated missions as well as by the ultra high-resolution spectroscopy such as the grating spectrometers proposed for IXO.

*[1] http://sms.msfc.nasa.gov/xenia/

References

Borgani, S. et al. 2004, MNRAS, 348, 1078
Branchini, E. et al. 2009, ApJ, 697, 328
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Dunkley, J., et al. 2009, ApJS, 180, 306
Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518
Hoshino, A. et al. 2009, this volume
Kaastra, J. S. et al. 2006, ApJ, 652, 189
Kull, A. & Böhringer, H. 1999, A&A, 341, 23
McCammon, D. et al. 2002, ApJ, 576, 188
Markevitch, M. et al. 2000, ApJ, 541, 542
Mitsuishi, I. et al. 2009, this volume
Nicastro, F. et al. 2005, ApJ, 629, 700
Ohashi, T. et al. 2006, SPIE, 6266, 62660G
Rasmussen, A. P. et al. 2007, ApJ, 656, 129
Takei, Y. et al. 2007, PASJ, 59, S339
Takei, Y. et al. 2008, ApJ, 680, 1049
Tawara, Y., et al. 2008, SPIE, 7011, 70111H
Yamasaki, N. 2009, this volume