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TRACING BRIGHT AND DARK SIDES OF THE UNIVERSE WITH X-RAY OBSERVATIONS

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ABSTRACT

X-ray observations of galaxy clusters have played an important role in cosmology, especially in determining the cosmological density parameter and the fluctuation amplitude. While they represent the bright side of the universe together with the other probes including the cosmic microwave background and the Type Ia supernovae, the resulting information clearly indicates that the universe is dominated by dark components. Even most of cosmic baryons turns out to be dark. In order to elucidate the nature of dark baryons, we propose a dedicated soft-X-ray mission, *DIOS* (Diffuse Intergalactic Oxygen Surveyor). Recent numerical simulations suggest that approximately 30 to 50 percent of total baryons at $z = 0$ take the form of the warm-hot intergalactic medium (WHIM) with $10^5\mathrm{K} < T < 10^7\mathrm{K}$ which has evaded the direct detection so far. The unprecedented energy resolution ($\sim$ 2eV) of the XSA (X-ray Spectrometer Array) on-board *DIOS* enables us to identify WHIM with gas temperature $T = 10^6 \sim 10^7\mathrm{K}$ and overdensity $\delta = 10 \sim 100$ located at $z < 0.3$ through emission lines of OVII and OVIII. In addition, WHIMs surrounding nearby clusters are detectable with a typical exposure time of a day, and thus constitute realistic and promising targets for *DIOS*.

Key words : cosmology – methods: numerical – X-rays

I. INTRODUCTION

More than 98 percent of the universe at $z = 0$ is *dark*; 23 percent in dark matter, 73 percent in dark energy (Spergel et al. 2003), and most of the baryons, which comprise the remaining 4 percent baryons, has largely evaded the direct detection so far (Fukugita, Hogan and Peebles 1998; see also Fig.1). Recent numerical simulations (Cen & Ostriker 1999a,b) indeed suggest that approximately 30 to 50 percent of total baryons at $z = 0$ take the form of the warm-hot intergalactic medium (WHIM) with $10^5\mathrm{K} < T < 10^7\mathrm{K}$ which does not exhibit strong observational signature. Figure 2 depicts snapshots of distribution of different species of matter in the universe at $z = 0$ from a smoothed hydrodynamic simulation in a Λ CDM universe (Yoshikawa et al. 2001); $\Omega_\mathrm{m} = 0.3$, $\Omega_\mathrm{b} = 0.015h^{-2}$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 1.0$, and $h = 0.7$, where Ω_m is the density parameter, Ω_b is the baryon density parameter, Ω_Λ is the dimensionless cosmological constant, σ_8 is the rms density fluctuation top-hat smoothed over a scale of $8h^{-1}$Mpc, and h is the Hubble constant in units of 100 km/s/Mpc. It employs 128^3 dark matter particles and the same number of gas particles in a comoving simulation cube of $L_\mathrm{box}^3 = (75h^{-1}\mathrm{Mpc})^3$. Clearly WHIM ($10^5\mathrm{K} < T < 10^7\mathrm{K}$; *lower right*) traces the large-scale filamentary structure of mass (dark matter) distribution (*Upper left*) more faithfully than hot intracluster gas ($T > 10^7\mathrm{K}$; *Lower left*) and galaxies (*Upper right*) both of which preferentially reside in clusters that form around the knot-like intersections of the filamentary regions. This implies that WHIM carries important cosmological information in a complementary fashion to distribution of galaxies (in optical) and of clusters (in X-ray).

II. DIOS: DIFFUSE INTERGALACTIC OXYGEN SURVEYOR

The dark components in the universe have very different implications in physics. The existence of dark matter has been established in astronomy for more than 30 years. The nature of dark matter is supposed to be deeply related to new physics beyond standard model. Thus its direct detection is recognized as one of the most important goals in experimental high-energy physics, which may be indeed feasible even in the next decade. While dark energy has an even longer history since Einstein introduced the cosmological constant in

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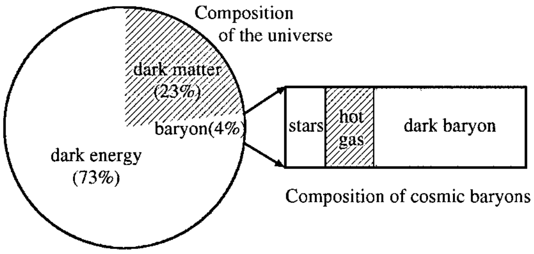

Fig. 1.— Composition of the universe and cosmic baryons

1917, its existence has attracted serious attention only around the end of the last century. The origin and the underlying physics of dark energy are even more challenging problems in physics than those of dark matter, the satisfactory understanding of which may require yet another century.

In contrast, the nature of baryons should be fully understood using 'old' physics, at least in principle. So the question why most of cosmic baryons is dark does not have to invoke 'new' physics but should be answered in astrophysics by properly putting together many pieces of 'known' physics. Moreover recent observational progress may enable to locate a fair fraction of dark baryons in the universe using their oxygen line emissions in the soft X-ray band.

While several groups have reported the detections of WHIM features using the conventional X-ray satellites including XMM-Newton and Chandra (c.f., Henry and Kaastra in these proceedings), the unambiguous detection and the detailed statistical characterization require a dedicated mission. *DIOS* (Diffuse Intergalactic Oxygen Surveyor) is such a mission currently under serious consideration in Japan (Ohashi et al. 2004; Suto et al. 2004). The primary scientific purpose is a systematic sky survey of WHIM using oxygen K emission lines, OVII (561eV:1s^2–1s2s), OVII (568eV:1s^2–1s2p), OVII (574eV:1s^2–1s2p), OVII (665eV:1s^2–1s3p) and OVIII (653eV:1s–2p). To this end, both unprecedented energy resolution ($\Delta E \approx 2$ eV) and large field of view are required. These features will be made possible by a combination of two innovations; a 4-stage X-ray telescope and a large array of TES (Transition Edge Sensor) micro-calorimeter. *DIOS* will also perform a mapping observation of the hot interstellar medium in our Galaxy. Taking advantage of the high energy-resolution, *DIOS* can detect the Doppler shifts of the hot interstellar gas with a velocity ~ 100 km s^{-1}, directly revealing the dynamics of heavy elements in hot bubbles in our Galaxy (galactic fountain).

III. WHIM IN THE LOCAL UNIVERSE

The detectability of WHIM through OVIII and OVII emission lines via *DIOS* was examined in detail by Yoshikawa et al. (2003). They concluded that within the exposure time of $T_{\rm exp} = 10^5 \sim 10^6$ sec *DIOS* will be able to reliably identify OVIII emission lines (653eV) of WHIM with $T = 10^6 \sim 10^7$ K and the overdensity of $\delta = 3 \sim 100$, and OVII emission lines (561, 568, 574, 665eV) of WHIM with $T = 3 \times 10^6 \sim 10^7$ K and $\delta = 10 \sim 100$. The WHIM in these temperature and density ranges is difficult to identify with the current X-ray observations except for the oxygen absorption features toward bright QSOs. *DIOS* is especially sensitive to the WHIM with gas temperature $T = 10^6 \sim 10^7$K and overdensity $\delta = 10 - 100$ up to a redshift of 0.3 without being significantly contaminated by the cosmic X-ray background and the Galactic emissions. The high-spectral resolution of *DIOS* turned out to be essential in identifying the redshifts of several WHIMs at different emission energies, i.e., Oxygen emission line tomography of the WHIMs at different locations.

As well as such a blind survey that is implicitly assumed in Yoshikawa et al. (2003), targeted observations of WHIM surrounding nearby clusters ($z < 0.03$) are also very important as discussed by Yoshikawa et al. (2004). They presented the analysis of mock observations using the constrained numerical simulation of the local universe by Dolag et al.(2003). Figure 3 plots the simulated all-sky maps of the bright side (X-ray continuum in 0.5–2 keV; *upper panel*) and of the dark side (OVII emission at 574 eV; *lower panel*) in the universe in the supergalactic coordinate. The maps reproduce well many known nearby structures, including the Great Attractor region, the Great Wall structure, the Pisces–Perseus supercluster, and the Local Void, as well as other rich clusters such as Virgo, A3627 and Coma. In contrast to the 0.5–2.0 keV X-ray emission, oxygen emissions preferentially come from small objects like galaxy groups and the outskirts of rich galaxy clusters and superclusters. Furthermore, as is clear for simulated Virgo and Pisces–Perseus in Figure 3, OVII (574 eV) emission avoids the very central regions of rich galaxy clusters. This is because the emissivity of OVII emission lines sharply drops beyond $T = 10^7$ K.

The simulation reproduces also many galaxy clusters and superclusters near the supergalactic equatorial plane. The left panel in Figure 4 show the simulated temperature field of a $9h^{-1}$Mpc thick slice parallel to the Super-Galactic plane, extending from SGZ $= -4.5h^{-1}$Mpc to SGZ $= 4.5h^{-1}$Mpc in real space. The right panel shows the simulated OVII surface brightness distribution on the supergalactic equatorial plane ($-15° <$ SGB $< 15°$) in redshift space (a vacant strip extending at SGL $= 0°$ and SGL $= 180°$ is due to the Galactic extinction).

Figure 5 plots the fraction of celestial areas in the local universe where OVII (*left*) and OVIII (*right*) line emissions exceed the given detection limit. Three filled patterns indicate the different ranges of the temperature mass-weighted over the "observed" regions. At lower temperature regions, the line emission is not necessarily responsible for all the mass inside the cell. Therefore, the mass fraction shown here does not follow the detected mass precisely and it should be rather

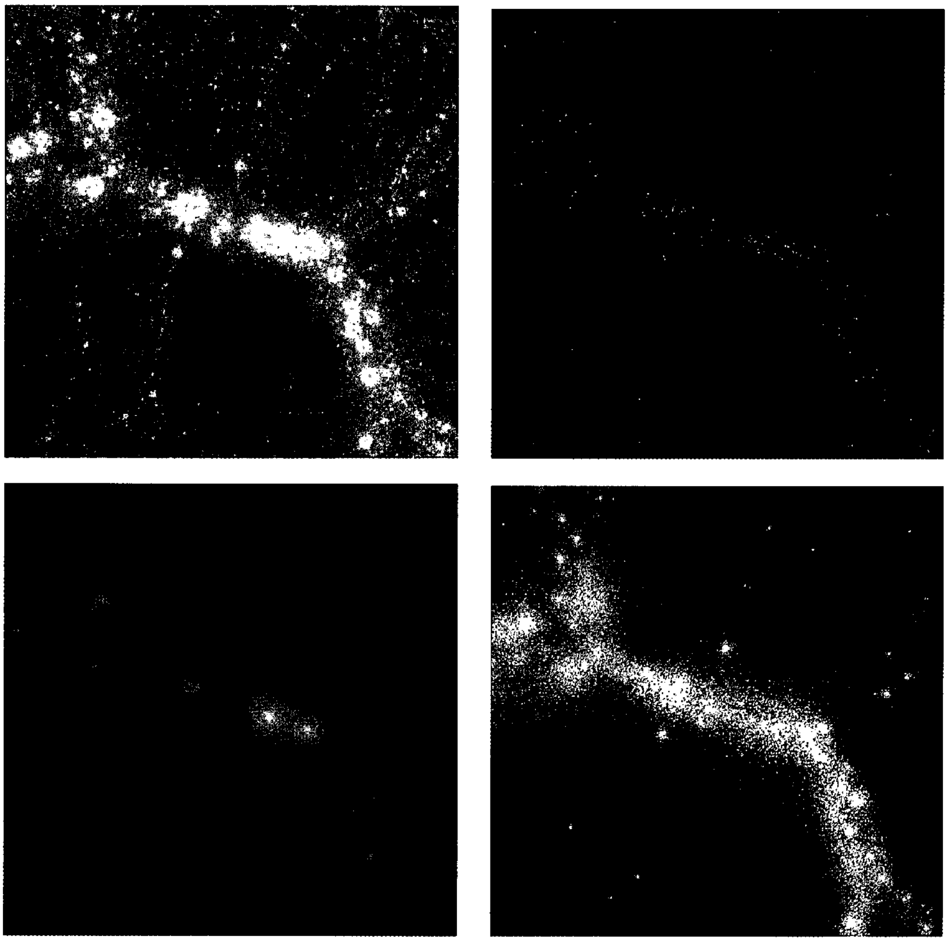

Fig. 2.— Simulated distribution of matter in the universe; *Upper-left:* dark matter, *Upper-right:* galaxies (cold baryon clumps below T^4K), *Lower-left:* hot intra-galactic medium ($T > 10^7$K), and *Lower-right:* warm-hot intergalactic medium ($10^5\mathrm{K} < T < 10^7\mathrm{K}$). The size of the plotted boxes corresponds to $30h^{-1}$Mpc $\times 30h^{-1}$Mpc with the depth of $10h^{-1}$Mpc.

interpreted as the upper limit of the "detected" fraction. These plots again indicate that more than 90 % of the "detected" mass has temperature higher than 10^6 K and that $\sim$ 60 % has temperature with $10^6\mathrm{K} < T < 10^7\mathrm{K}$. Since baryons with $T > 10^7$ K are detectable through continuum X-ray emission by conventional X-ray missions, previously unexplored and detectable only through the oxygen emissions will be about 20 % if we adopt the nominal detection limit of *DIOS*, 10^{-11}erg s^{-1} cm^{-2} sr^{-1}.

For the detection of WHIM through its emission, outskirts of rich galaxy clusters are the most promising regions for the targeted survey. We estimate the probability that OVIII (653 eV) and OVII (574 eV) line emissions are brighter than a given limiting flux within a 0.5° × 0.5° region around rich galaxy clusters, Coma, Perseus, Hydra, A3627 and Centaurus clusters. Incidentally figure 3 indicates that the brightest oxygen emission in this simulation comes from Virgo cluster. However, considering the 2eV energy resolution of XSA on-board *DIOS*, the minimum redshift of an extra-galactic oxygen line emitter where it can be discriminated from the Galactic oxygen emission is $z_{\mathrm{min}} \simeq (2\mathrm{eV}/600\mathrm{eV}) = 0.0033$. Therefore, oxygen emission lines of Virgo cluster at redshift $z = 0.0038$ will be seriously contaminated by the strong Galactic oxygen emission. Thus unfortunately Virgo cluster does not seem to be an ideal target for *DIOS*.

Figure 6 shows such probabilities for those regions whose separation r_s from cluster centers is $r_s < 1h^{-1}$Mpc, $1h^{-1}\mathrm{Mpc} < r_s < 2h^{-1}$Mpc, and $2h^{-1}\mathrm{Mpc} < r_s < 4h^{-1}$Mpc. Near the central regions of galaxy clusters, OVII emission cannot be detected so frequently as OVIII emission because the emissivity of OVII rapidly drops at high temperature $T > 10^7$K. Approximately (20–30)% area of the outskirts of known galaxy clusters ($1h^{-1}\mathrm{Mpc} < r_s < 4h^{-1}$Mpc) in the local universe (Coma, Hydra, Centaurus, A3627, and Perseus) ex-

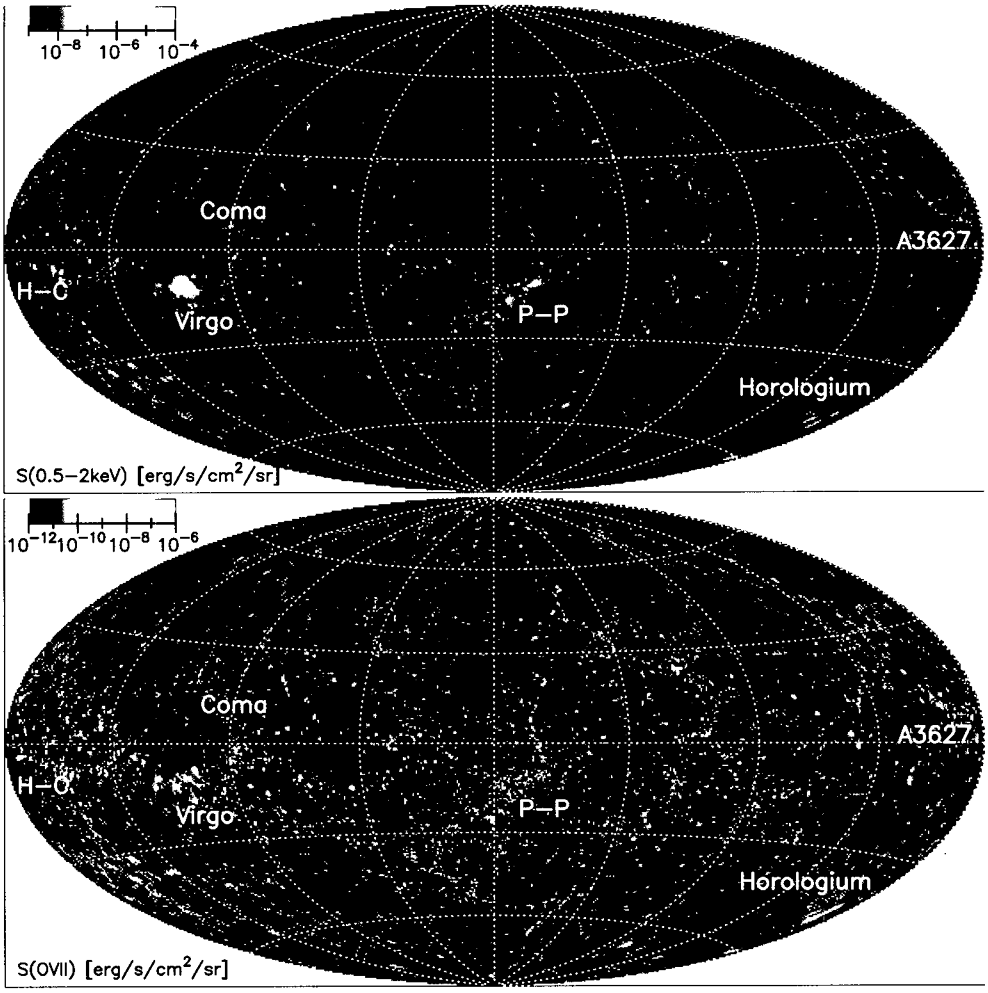

Fig. 3.— All-sky maps of X-ray continuum (0.5–2keV) (*upper*) and OVII (574 eV) (*lower*) emissions in the supergalactic coordinate.

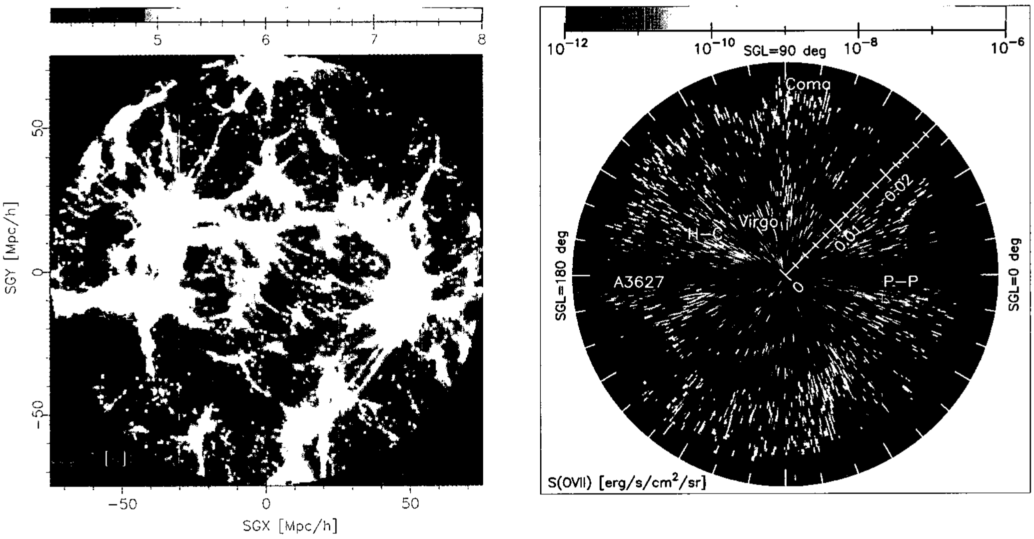

Fig. 4.— Projected maps of temperature (*left*) and OVII surface brightness (*right*) in the simulated local universe on the supergalactic plane.

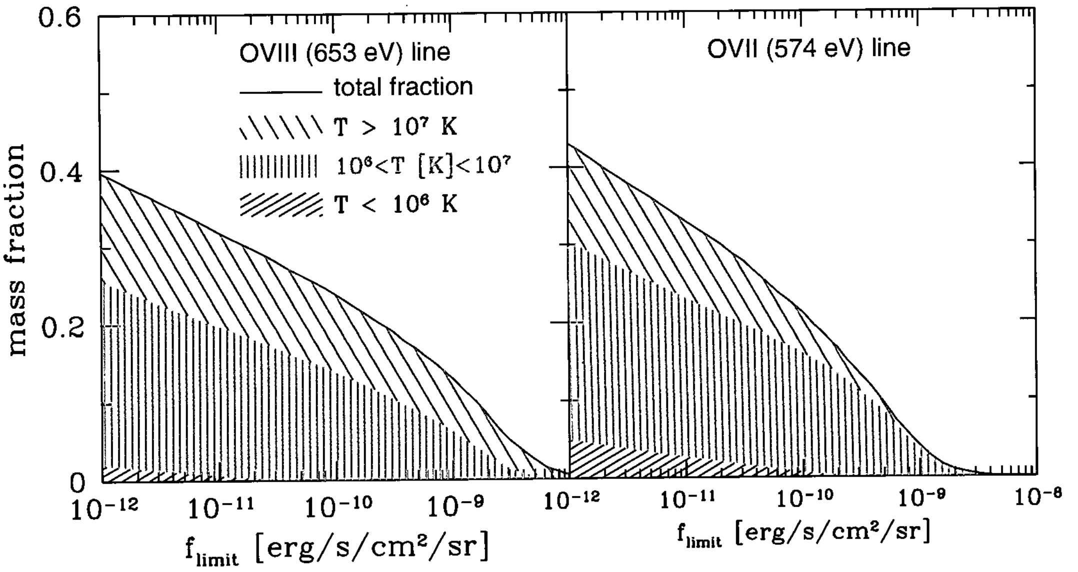

Fig. 5.— Baryon mass fraction detected through OVII (574 eV) (*right*) and OVIII (653 eV) (*left*) emission lines. Contributions of baryons with $T < 10^6$ K, $10^6\mathrm{K} < T < 10^7\mathrm{K}$, and $T > 10^7\mathrm{K}$ are shown separately.

ceeds the nominal detection limit of *DIOS* (10^{-11} erg s^{-1} cm^{-2} sr^{-1}) for OVII and OVIII emissions.

We note here that all the results presented here assume the collisional ionization equilibrium. In reality, however, the validity of this assumption at the density and temperature ranges relevant for WHIM is not clear. Thus further careful consideration of radiative processes need to be done. For instance, Kang et al. (2004) considered the effect of the photo-ionization background on the oxygen emission from WHIM, and Yoshida et al. (2004) pointed out that the majority of WHIM is still in the two-temperature phase where the electron temperature is much below the shock-heated ion temperature. We are currently working on improving the thermal physics of WHIM assumed in Yoshikawa et al.(2003, 2004), which will be presented elsewhere (Kawahara et al. 2004).

IV. DISCUSSION

Approximately 30 to 50 percent of the total baryons in the present universe is supposed to take a form of warm/hot intergalactic medium (WHIM) whose X-ray continuum emission is very weak. In order to carry out a direct and homogeneous survey of elusive cosmic missing baryons, we propose a dedicated soft-X-ray mission, *DIOS* (Diffuse Intergalactic Oxygen Surveyor).

We have presented a complementary role of a dedicated soft X-ray mission to search for cosmic missing baryons, *DIOS*, in exploring the (currently) dark side of the universe. In particular we have examined the possibility to locate the Warm-Hot Intergalactic Medium in the nearby universe on the basis of the constrained numerical simulations. We found that several filamentary structures around nearby clusters in the local universe are plausible and promising targets for the WHIM search with *DIOS*. Thus their targeted survey plays a complementary role to the blind survey for WHIM located at $0.0 < z < 0.3$. In those regions both OVII and OVIII emissions are likely to be identified simultaneously, and one can use their line ratio as a diagnostics for the nature of the observed WHIM, in particular its temperature. We also found that we will be able to detect OVII or OVIII emission in approximately (20–30)% area of the outskirts of known galaxy clusters in the local universe (Coma, Hydra, Centaurus, A3627, and Perseus). In conclusion, *DIOS* promises to open a new window of detection and characterization of cosmic missing baryons located at nearby and distant universe, and to provide yet another important and complementary tool to trace the large-scale structure of the universe.

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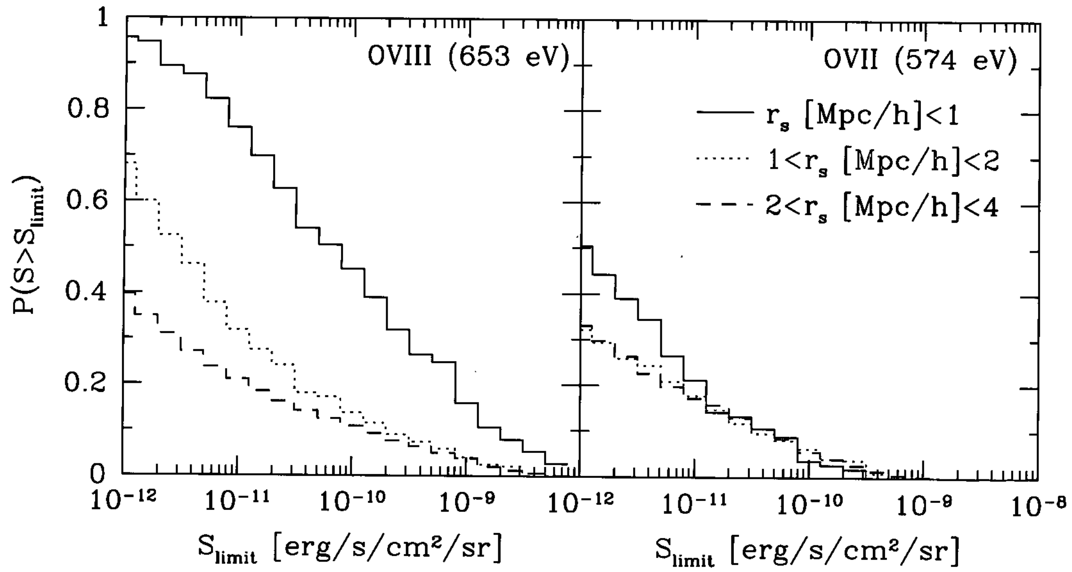

Fig. 6.— Cumulative distribution of the oxygen flux for a 0.5° × 0.5° region separated from rich galaxy clusters; (*Left*) for OVIII, and (*Right*) for OVII. Different lines correspond to the different regions of radius r_s away from the center of those clusters; $r_s < 1\,h^{-1}$Mpc (*solid*), $1\,h^{-1} < r_s < 2\,h^{-1}$Mpc (*dotted*), and $2\,h^{-1} < r_s < 4\,h^{-1}$Mpc (*dashed*).

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