X-ray Spectroscopy of the Warm-Hot Intergalactic Medium

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Abstract

Theoretical studies suggest that highly ionized warm and hot extragalactic gas is an important component of the baryonic Universe at the current epoch. Study of this putative Warm-Hot Intergalactic Medium at small redshift will require a broad-based observational strategy, due to the extremely heterogeneous nature of the medium, and the likelihood that much of it is not relaxed. We argue that an indispensible component of such a strategy is a survey based on wide field, high spectral resolution, soft X-ray emission line imaging in transitions of highly ionized C, O, Ne, and Fe, coupled with sensitive, high resolution absorption spectroscopy.

1 Introduction: A Highly Ionized Intergalactic Medium

The history of the highly ionized intergalactic medium (IGM), however little we know about this medium, has had a checkered history. In his survey of the intergalactic matter content of the Universe, George Field discussed the evidence for a hot IGM from the then-recently measured intensity of the X-ray background (Field 1972). Interpreted as thermal bremsstrahlung from hot gas, the measured intensity indicated a total mass density that could be as high as the critical density of the Universe. Subsequently, in a famous observation of the bright BL Lac object PKS2155−304, Canizares and Kruper detected a narrow absorption feature near photon energy 600 eV in its X-ray spectrum observed with the *Einstein* Objective Grating Spectrometer (Canizares and Kruper 1984). Interpreted as intergalactic H-like Oxygen Lyα absorption broadened by the expansion of the Universe, the total amount of absorption again indicated a gas density that could be as high as the critical density. But this absorption feature was never seen again, nor was anything like it ever seen in any other object. Meanwhile, accurate measurements of the shape of the cosmic microwave background have of course shown that it is indistinguishable from blackbody, firmly limiting any distortions arising from Compton scattering by diffuse hot gas (other than in overdense regions). In a final case of Cosmic Irony, a far infrared rocket experiment conducted shortly before *COBE* was launched *did* detect a large Comptonization bump, indicating the existence of a huge reservoir of hot intergalactic gas (Matsumoto et al. 1988), but the bump was not confirmed by *COBE* and must have been due to a subtle instrumental effect.

The IGM does show up in discrete (Hydrogen) Lyα absorption of course (and in other species), both at high and low redshifts. And, final irony, now that we know that the baryon density constitutes only a small fraction of the total mass-energy density of the Universe, the density of intergalactic H indeed dominates the baryon density, at high redshifts (*e.g.* Fukugita, Hogan, and Peebles 1998). At small redshifts, the situation appears more complex and puzzling.

A careful inventory of the baryons in the local Universe indicates that the total baryon density in stars and gas in galaxies, groups, and clusters, and in diffuse intergalactic matter falls short of the baryon fraction measured at $z \sim 3$ by up to 50% (Fukugita and Peebles 2004). Independently, large scale simulations of the evolution of Dark Matter and gas, initiated by Cen and Ostriker, showed that a large fraction of the high-redshift Lyα forest could have been turned into a highly ionized 'Warm-Hot Intergalactic Medium' (WHIM), which would easily have escaped detection (Cen and Ostriker 1999). Most likely, this is the solution to the 'missing baryon problem'.

2 The Warm-Hot Intergalactic Medium

The properties of the WHIM, as found in large-scale DM/Hydro simulations, can very roughly be characterized as follows. Diffuse gas starts to fall into the gravitational potential of the large-scale matter distribution, and encounters shock waves as it does so. The gas is heated to temperatures between 10^5 and 10^7 K as it gathers in regions of overdensity $10-100$ (with respect to the mean matter density of the Universe; for reference, at the current epoch the mean baryon density is $\langle n_b \rangle = 2 \times 10^{-7}$ cm^{-3}). At each temperature, there is of order unity dispersion in the logarithm of the density, or, at each density, there is a spread of order unity in the logarithm of the temperature, around an average of about 10^6 K.

As to the metal enrichment of the medium, essentially nothing is known experimentally, other than that the high redshift Lyα forest can have metal abundances as low as 0.1% Solar (but *does* contain metals), and the intracluster medium at small redshifts has a remarkably consistent average metallicity of $\sim$ 30% solar. Simulations with parameterized star formation, metal production, and dispersal mechanisms and rates indicate that the metal content of the IGM should be highly inhomogeneous, strongly density-dependent, and range between $3 \times 10^{-3} - 1.0$ Solar (*e.g.* Cen and Ostriker 2006). In fact, there is ample observational evidence for an intricate cycling of metals between galaxies and the IGM, from high redshifts down to the present (see Pettini 2004 for a review).

One feature that is beyond doubt is that the WHIM will be highly ionized, making it very hard to detect. H is very highly ionized, but it does show up in Lyα absorption in selected sight lines as broad and shallow absorption lines (*e.g.* Richter et al. 2008). Likewise, far UV spectroscopy reveals ubiquitous absorption by highly ionized Oxygen in the IGM, in the form of O VI $n = 2-2$ $\lambda\lambda 1032, 1038$ Å absorption (Tripp et al. 2008, and references therein). Absorption by the corresponding ionization stage of Ne has been seen in the UV (Ne VIII; Savage et al. 2006). But the bulk of the metals will be in the higher H- and He-like ionization stages, of which the ground state transitions are all in the soft X-ray band.

The current generation X-ray spectrometers are not powerful enough to address this problem in general. X-ray absorption has been seen in isolated instances (towards Mkn 421; Nicastro et al. 2005; towards H2356−309, through the Sculptor Wall; Buote et al. 2009), but at the limits of detectability. Likewise, there is one instance of a filament-like structure seen in X-ray emission, between the clusters Abell 222 and 223 (Werner et al. 2008). Other than these observations, no data on the high-ionization phase of the IGM exists, and since the expected X-ray absorption line contrasts and surface brightnesses are small, none will exist without dedicated experiments.

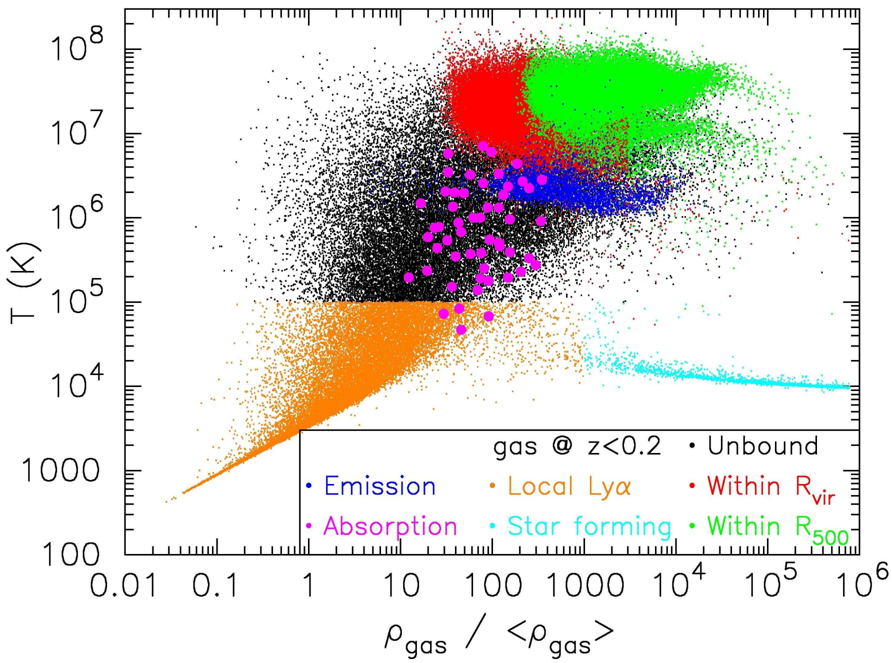

Figure 1: Density-temperature phase plane of the intergalactic medium at small redshifts, derived from coupled large-scale Dark Matter/Hydrodynamics simulations. The distribution of points reflects the fate of gas elements in the primordial Warm-Hot IGM on its first infall. The black and blue dots represent phases currently observationally not accounted for, containing potentially up to half the baryon mass at the current epoch. The effect of feedback by star forming galaxies, in the form of fast, hot outflows (galactic Superwinds) will be to populate the region $\delta < 30$, $4 \times 10^4 < T < 4 \times 10^7$ K with metal-rich gas, located close to the galaxies.

3 The Astrophysics of the WHIM

The basic properties of the IGM are most conveniently discussed in terms of the density and temperature as independent variables. In the 'primordial' WHIM (the gas falling into the filaments and clusters of the large-scale structure for the first time), a gas element initially adiabatically expands with the Universal expansion, from an initial $\sim 10^4$ K photoionized state at the end of Cosmic Reionization. It breaks off from the expansion, and starts falling in, encountering shocks as it does so, and jumping up in temperature and density. Ultimately, a fraction of the gas travels all the way up to the intracluster medium, at $T > 10^7$ K, overdensity $\delta > 500$.

From numerical simulations, it has become clear that the landscape in the temperature-density plane is heavily affected by feedback from galaxies (Cen and Ostriker, 1999, 2006), often referred to as galactic Superwinds (GSW). Calculations that include this feedback in a semi-analytical way (meaning, the source of metals and kinetic energy is parameterized, but the subsequent evolution of the expelled material is calculated explicitly) show that bubbles of hot, high-metallicity gas surround the galaxies, and the familiar filamentary web-like structure seen in the gas density distribution in fact has spines of hot, high metallicity gas. In the temperature-density plane, the low-density, high temperature region is filled almost exclusively by this GSW material, and of course it contains the largest metal abundances (up to Solar).

But the most striking property of the WHIM is its extremely low density, lower than any other medium studied in astrophysics. This low density makes for a number of unusual complexities. The relaxation timescales for a number of important processes that affect the local evolution of the WHIM are in fact comparable to, or exceed, the age of the Universe (Yoshida et al., 2005; Cen and Fang 206; Yoshikawa and Sasaki 2006; Bykov et al. 2008). A large fraction of the metal mass may not be in ionization equilibrium, and its ionization may mostly be driven by photoionization by the X-ray background, rather than by collisional ionization following heating of the electrons at the shocks. It may exhibit signs of incomplete equilibration of electrons and ions at shocks, potentially showing effects associated with the first amplification of intergalactic magnetic fields (*e.g.* Dolag et al., 2008 and references therein). It may end up being thermally unstable, generating a 'second-generation' filamentary structure (*e.g.* Kritsuk and Norman 2002). Since all these deviations from equilibrium are strongly dependent on density and past history, they present both obstacles and unique opportunities: they make measurement of the physical properties of the WHIM more difficult, which means we will require multiple diagnostics, while at the same time, they directly encode information that is lost in equilibrium situations.

4 Determining the Physical Properties of the WHIM

The WHIM will turn out to be an extremely inhomogeneous medium, and determining its basic properties from imaging and spectroscopy dictates a careful, multi-disciplinary and multi-wavelength observational strategy. The basic ingredients of such a strategy are as follows.

High-resolution sensitive UV spectroscopy is needed to find broad Lyα absorption, and O VI-bearing gas. Hydrogen is the majority constituent, and a measure of its total mass is needed in order to estimate abundances and metal masses, no matter how difficult the measurement (the lines are broad and shallow). Any experiment designed to probe the highly ionized gas will have to seek synergy with the data generated by the *Cosmic Origins Spectrograph* on HST. Likewise, UV spectroscopy will probe the Li-like ions of the abundant low-Z elements, which trace the fraction of gas up to temperatures of $\sim 6 - 8 \times 10^5$ K. In general, UV spectroscopy can take advantage of the high resolving powers that can be realized in this band (and therefore the excellent sensitivity and velocity resolution), due to fact that background continuum source photon fluxes are higher in the UV than in the X-ray, and focusing and diffraction of UV radiation requires less extreme (and inefficient) optics than X-rays. For model-independent measurements of the H and low-Z ion distribution, the absorption spectroscopy would have to be complemented by emission line imaging, in order to obtain densities and linear sizes from measured absorption column densities and emission measures.

X-ray spectroscopy is essential to probe the highest ionization stages of the WHIM, where most of the matter resides, to fully lay out its properties and its dynamical, chemical, and thermodynamical history, and to determine its relation to the other baryonic components of the Universe. This applies to the primordial WHIM as well as to the GSW-blown material. *High resolution X-ray absorption spectroscopy* of sight lines to bright background continuum sources will be sensitive to the lower-overdensity end of the WHIM (since absorption line contrasts scale with density, while emission line intensities will scale with the square of the density). In practice, high spectral resolution, capable of resolving the expected velocity broadening and shifts, is most readily achieved with diffraction grating spectrometers, such as the X-ray Grating Spectrometer (*XGS*) designed for the *International X-ray Observatory*.

Finally, **an essential complement to the long-wavelength studies and X-ray absorption spectroscopy will be a sensitive, high spectral resolution, soft X-ray imaging spectrometer with a large field of view**. Such an instrument, with capabilities that can in practice not be realized in traditional mission designs based on large focal length telescopes, can image the distribution of diffuse, highly ionized gas. High spectral resolution will allow redshift- and velocity-resolved imaging in narrow metal emission lines, yielding the 3D distribution and the peculiar velocity fields imprinted on the highly ionized gas.

Spectral resolution, both in absorption and in emission, is crucial in this context for several reasons, other than the 3D imaging (Paerels et al. 2008). First, the density in the WHIM is extremely low, and the expected surface brightness in the strongest emission lines (the $n = 1 - n'$ lines in the H- and He-like ions of O, C, and Ne; and maybe the strongest $n = 2-3$ emission line of Ne-like Fe) is extremely low. *Without the advantage of high spectral resolution to isolate the line emission, the X-ray emission contrast will be too low to ever be observable against the pervasive backgrounds of unresolved continuum point sources, diffuse thermal Galactic and circum-Galaxy and Local Group X-ray emission, and the instrumental backgrounds.* Second, in order to determine model-independent properties of the medium (densities, masses, velocity fields, abundances, etc.), *joint high resolution emission and absorption spectroscopy is crucial.* Absorption line strengths will scale with column density, while emission line surface brightness will scale with linear emission measure, so joint measurement of both yields estimates for volume densities and linear sizes; large resolving power is essential to detect the faint absorption and emission lines. Third, as indicated above, the fact that the conditions in the WHIM are likely to be complex and possibly not in equilibrium requires access to multiple spectral diagnostics (for instance, measurement of the complete ionization balance, distinguishing photoionization from collisional ionization, etc.; *e.g.* Paerels 1999 and references therein). Finally, there will be a strong foreground, both in absorption and emission, by hot gas in and around our Galaxy, and spectral resolution is needed to separate these foregrounds from the true intergalactic signal.

5 Requirements for X-ray Imaging and Absorption Spectroscopy

We take spectroscopy of the H- and He-like ions of Oxygen as our fiducial example. Oxygen is abundant, and its K-shell spectra are simple, and are located in a spectral region that is otherwise clean. In the absence of additional Doppler broadening, the thermal broadening at $T \sim 10^6$ K is so narrow that the strongest Oxygen absorption lines will saturate at very modest velocity widths, and at small column densities. Filaments of cross section ~ 1 Mpc, at overdensities of 10 or more (assuming 10% Solar abundance) will have saturated $n = 1 - 2$ absorption lines. The corresponding equivalent widths are of order 30 km s^{-1} (or 0.05 eV, or 2 mÅ), which suggests that resolving power approaching $R \sim 10,000$ is required. In practice, peculiar velocity fields of up to several hundred km s^{-1} are probably present,

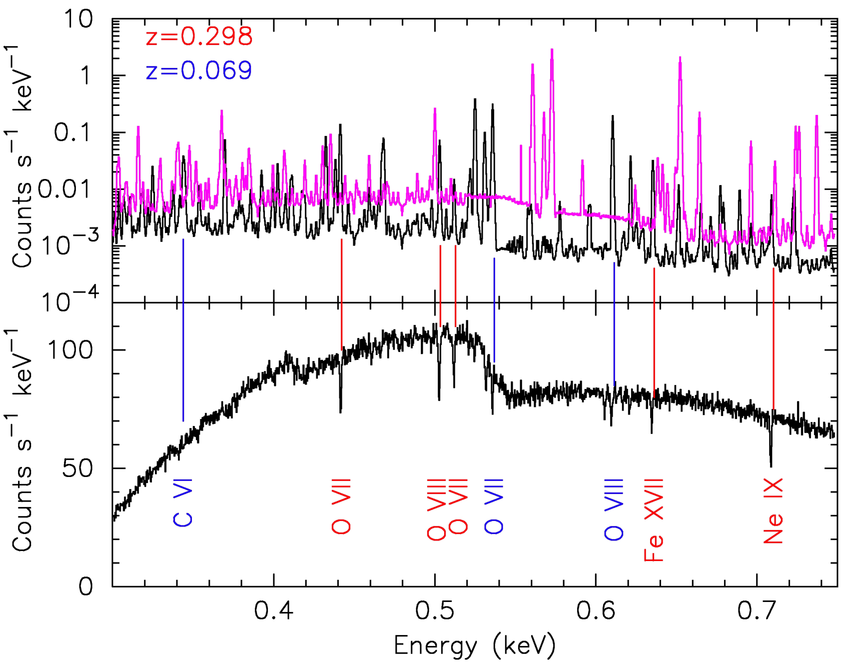

Figure 2: The power of combined X-ray absorption and emission line spectroscopy of the Warm-Hot IGM. The lower simulated spectrum shows absorption towards a bright Gamma-Ray Burst afterglow, detected at 2 eV energy resolution, revealing two absorption line systems in H- and He-like Oxygen, Carbon, Fe, and Ne, at $z = 0.069, 0.298$. The upper spectrum shows the corresponding emission line spectrum, as detected with instrumentation as designed for *Xenia*, or comparable. Unrelated line emission originates in the local Galactic and circumgalactic environment. Joint absorption and emission spectroscopy eliminate ambiguity, increase significance, and provide complementing physical and astrophysical diagnostics on the state of the gas.

which would reduce the resolving power requirement to a few thousand. *These requirements suggest that X-ray absorption spectroscopy of the IGM should be pursued with a diffraction grating spectrometer of resolving power $R \sim 3000$, on a telescope with a large effective area.* Absorption spectroscopy with cryogenic spectrometers with practicable resolving powers ($\Delta E \sim 2$ eV), while certainly sensitive to the larger column densities, cannot probe the smallest columns, nor will it be robustly sensitive to the expected velocity fields. The diffraction grating spectrometer projected for the *International X-ray Observatory* satisfies these requirements.

Emission line imaging spectroscopy should be pursued *with a large field of view (of order one degree), short focal length, large grasp (effective area times field of view) soft X-ray telescope, with a high resolution imaging X-ray spectrometer at the focus.* The expected emission line intensities are very small. A simple estimate (Paerels et al. 2003) suggests that H- and He-like Oxygen $n = 1 - 2$ line emission will have an average surface brightness of order $0.1 - 1$ photon cm^{-2} s^{-1} sr^{-1}, and a successful experiment will need a grasp of order several hundred cm$^2\cdot$ deg^2, and a spectral resolution of order $1 - 2$ eV or better; the latter is feasible with current-generation cryogenic X-ray spectrometers (microcalorimeters). Angular resolution is important, in order to spatially separate emission from the SWG-blown bubbles from the primordial WHIM, and should be of order 20-30 arcsec or better.

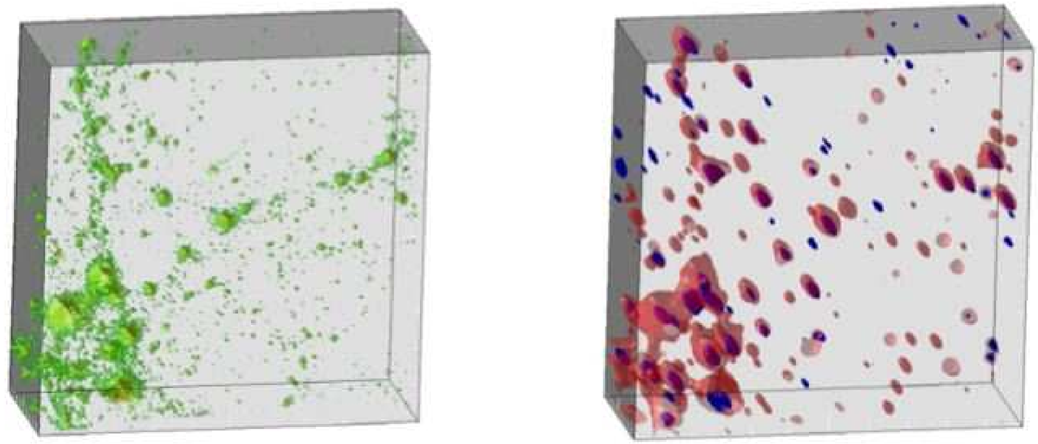

Figure 3: X-ray emission line imaging spectroscopy provides a 3D, high-contrast map of Oxygen-line emitting gas. The left panel shows the result of a simulation of a 5×5 deg (38.5 Mpc on a side), $z = 0.11 - 0.13$ slice of the Universe, showing the density distribution in the Warm-Hot IGM. The right panel shows the detection of Oxygen line emission (at 2 eV spectral resolution); blue regions indicate volume elements with $> 5\sigma$ significance on the line detection against background. The red volume shows the regions of overdensity $\delta > 5$, for comparison.

These joint requirements are in fact met by the mission design for *Xenia*, which will be designed to also take advantage of X-ray absorption spectroscopy, by using Gamma-Ray Burst afterglows as a 'renewable resource'. Two figures illustrate the potential of X-ray absorption- and emission line spectroscopy for study of the Warm-Hot Intergalactic Medium (Figures 2 and 3). With a grasp of 700 $\mathrm{cm}^2 \cdot \mathrm{deg}^2$ and imaging spectroscopy at 2 eV energy resolution, up to 30-40% of the mass in the WHIM down to overdensities below $\delta \sim 100$, can be surveyed (Takei et al. 2009).

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