X-RAY OBSERVATIONS OF THE HOT INTERGALACTIC MEDIUM

Q. DANIEL WANG
Dearborn Observatory, Northwestern University
2131 Sheridan Road, Evanston, IL 60208-2900
e-mail: wqd@nwu.edu

1. Introduction

A definite prediction from recent N-body/hydro simulations of the structure formation of the universe is the presence of a diffuse hot intergalactic medium (HIGM; e.g., Ostriker & Cen 1996). The filamentary structure of the today's universe, as seen in various galaxies surveys, is thought to be a result of the gravitational collapse of materials from a more-or-less uniform and isotropic early universe. During the collapse, shock-heating can naturally raise gas temperature to a range of $10^5 - 10^7$ K. Feedbacks from stars may also be an important heating source and may chemically enrich the HIGM. The understanding of the heating and chemical enrichment of the IGM is critical for studying the structure and evolution of clusters of galaxies, which are nearly virialized systems (e.g., Kaiser 1991; David, Jones,& Forman 1996). Most importantly, the HIGM may explain much of the missing baryon content required by the Big Bang nucleosynthesis theories (e.g., Copi, Schramm, & Turner 1995); the total visible mass in galaxies and in the hot intracluster medium together is known to account for $\lesssim 10\%$ of the baryon content (e.g., Persic & Salucci 1992).

What are the probable observational signatures of the HIGM? First, the HIGM may contribute considerably to the soft X-ray background. Various emission lines of heavy elements (O, Ne, and Fe) may collectively form a distinct spectral bump at ~ 0.7 keV (Cen et al. 1995). This bump has the potential as a diagnostic of the physical and chemical properties of the HIGM. Second, the density and temperature of the HIGM can be greatly enhanced in filamentary superstructures near rich clusters of galaxies because of deep gravitational potential. In these superstructures, X-ray emission from the HIGM can be greatly enhanced.

K. Koyama et al. (eds.), The Hot Universe, 193-196.
© 1998 *IAU. Printed in the Netherlands.*

https://doi.org/10.1017/S0074180900114743 Published online by Cambridge University Press

Here I review lines of observational evidence for the HIGM. These results appear to be consistent with the predictions from the simulations, and demonstrate the potential of X-ray observations as a powerful tool to study the large-scale structure of the universe.

2. Point-like versus Diffuse X-ray Components

While $\gtrsim 75\%$ of the background in the 1 - 2 keV range is apparently due to point-like sources (AGNs; Hasinger et al. 1993), the point-like contribution to the background decreases considerably at lower energies. Dick McCray and I have conducted an auto-correlation function (ACF) analysis of the X-ray background, based on *ROSAT* observations (Wang & McCray 1993). Using a multi-energy band ACF analysis technique, we characterized the mean spectrum of point-like sources, below a source detection limit of $S(0.5-2\ \mathrm{keV}) \sim 1\times10^{-14}$ ergs s^{-2} cm^{-2}, as a power law with $\alpha = 0.7\pm0.2$. This spectrum is significantly flatter than that of the observed background. We find that point-like sources cannot account for more than about 60% of the background in the M-band ($\sim 0.4 - 1$ keV) without exceeding the total observed flux in higher energy bands. To explain the background spectrum, an additional thermal component of a characteristic temperature of $\sim 2 \times 10^6$ K is required, in addition to the well-constrained local 10^6 K component.

3. Spectroscopic Evidence for a Thermal Component

Direct evidence for a *thermal* M-band component of the background comes from the *ASCA* X-ray Observatory, which provides spectroscopic capability between 0.4-10 keV. The *ASCA* spectrum of the X-ray background clearly shows an excess in the M-band range above the extrapolation of the power law ($\alpha \approx 0.4$) that fits well to the 1-10 keV spectrum. The excess also shows signs of OVII and OVIII lines, suggesting that at least part of it is thermal in origin (Gendreau et al. 1995). There are, however, some significant discrepancies (up to $\sim$ 30%) between soft X-ray background normalizations derived from different instruments (McCammon & Sanders 1990; Wu et al. 1991; Garmire et al. 1992; Gendreau et al. 1995; Snowden et al. 1995), making it hard to compare different measurements of absolute background intensities. Nevertheless, both the *ROSAT* ACF analysis and the *ASCA* spectrum do seem to suggest that a considerable fraction of the M-band background arises in diffuse thermal gas. The question is where the gas is located: Galactic or extragalactic?

https://doi.org/10.1017/S0074180900114743 Published online by Cambridge University Press

4. Galactic Foreground versus Extragalactic Background

While the extragalactic nature of the hard X-ray background in the 1 - 100 keV range is now generally accepted, a considerable Galactic contribution is *expected* at lower energies. X-ray shadowing studies are probably the only viable approach to separate the Galactic foreground from the extragalactic background. Such studies have yielded various estimates of the extragalactic background intensity in the range of 26 - 62 keV s^{-1} cm^{-2} keV^{-1} sr^{-1} at $\sim$ 0.25 keV (e.g., Snowden et al. 1994; Cui et al. 1996; Barber, Roberts, & Warwick 1996). The uncertainty in these estimates is still too large, however, to place a useful constraint on the diffuse HIGM contribution.

We have recently measured the extragalactic background at $\sim$ 0.7 keV by observing the X-ray shadowing of a neutral gas cloud in the Magellanic Bridge region (Wang & Ye 1996). The cloud is at a distance of $\sim$ 60 kpc and has a peak HI column density of a few times 10^{21} cm^{-2}. From the anti-correlation between the observed background intensity and the HI column density of the cloud, we derived an unabsorbed extragalactic background intensity as $\sim$ 28 keV s^{-1} cm^{-2} keV^{-1} sr^{-1} at $\sim$ 0.7 keV, with the 95% confidence lower limit as 18 keV s^{-1} cm^{-2} keV^{-1} sr^{-1}. Part of this extragalactic emission must come from point-like sources such as AGNs. But the average spectrum of point-like sources is significantly flatter than that of the background and apparently flattens with decreasing source fluxes, as shown in our ACF analysis. Using the total observed background intensity in the 1-2 keV band, we obtain an upper limit to the source contribution as $\lesssim 14$ keV s^{-1} cm^{-2} keV^{-1} sr^{-1}, which is smaller than the 95% confidence lower limit of the measured extragalactic background (i.e., $18 - 14 = 4$ keV s^{-1} cm^{-2} keV^{-1} sr^{-1}). Although the actual intensity of the diffuse component is still greatly uncertain, our measurement is consistent with the HIGM contribution to the M-band background as predicted with popular cosmological models (Cen et al. 1995).

5. HIGM Features near Rich Clusters

As illustrated in the simulations, one may also expect to detect enhanced X-ray-emitting filamentary superstructures near rich clusters of galaxies. In a pilot study of the environs of intermediate redshift clusters, A. Connolly, R. Brunner, and I (1997) have discovered that A2125 is within a filamentary complex consisting of various extended X-ray-emitting features. We have further made a multi-color optical survey of galaxies in the field, using the Kitt Peak 4-m telescope. The color distribution of galaxies in the field suggests that this complex represents a hierarchical superstructure spanning $\sim 11h_{50}^{-1}$ Mpc at redshift $\sim$ 0.247. The multi-peak X-ray morphology of A2125 suggests that the cluster is an ongoing coalescence of at least

https://doi.org/10.1017/S0074180900114743 Published online by Cambridge University Press

three major subunits. The dynamic youth of this cluster is consistent with its large fraction of blue galaxies observed by Butcher & Oemler (1984). The complex also contains two additional clusters. But the most interesting feature is the large-scale low-surface-brightness X-ray emission from a moderate galaxy concentration associated with the complex.

This hierarchical complex, morphologically and spectrally very similar to superstructures seen in various N-body/hydrodynamic simulations (e.g., CDM+Λ universe; Cen & Ostriker 1994). We find that such superstructures can naturally explain the positive cross-correlation function between nearby Abell clusters and the X-ray background surface brightness at ~ 1 keV, as detected by Soltan et al. (1996).

While these results have offered us a first glimpse of the HIGM, observations with upcoming X-ray observatories such as AXAF, XMM, and Astro-E, will enable us to greatly improve the measurements. Detailed comparisons with the simulations will become possible, providing unique information on various physical and chemical processes of the structure formation of the universe.

6. References

Barber, C. R., Roberts, T. P., & Warwick, R. C. 1996, MNRAS, 282, 157
Butcher, H., & Oemler, Jr. A. 1984, ApJ, 285, 426
Cen, R., & Ostriker, J. P. 1994, ApJ, 429, 4
Cen, R., Kang, H., Ostriker, J. P., & Ryu, D. 1995, ApJ, 451, 43
Copi, C. J., Schramm, D. N., & Turner, M. S. 1995, Science, 267, 192
Cui, W., et al. 1996, ApJ, 468, 117
David, L. P., Jones, C., & Forman, W. 1996, ApJ, 473, 692
Garmire, G. P., et al. 1992, ApJ, 399, 694
Gendreau, K. C., et al. 1995, PASJ, 47, L5
Hasinger, G., et al. 1993, A&A, 275, 1
Kaiser, N. 1995, ApJ, 383, 104
McCammon, D., & Sanders, W. T. 1990, ARA&A, 28, 657
Ostriker, J. P., & Cen, R. 1996, ApJ, 464, 27
Persic, M., & Salucci, P. 1992, MNRAS, 258, 14p
Snowden, S. L., et al., 1994, ApJ, 430, 601
Snowden, S. L., et al., 1995, ApJ, 454, 643
Soltan, A. M., et al. 1996, A&A, 305, 17
Wang, Q. D., Connelly, A., & Brunner, R. 1997, ApJL, 487, 13
Wang, Q. D., & McCray, R. 1993, ApJL, 409, 37
Wang, Q. D., & Ye, T. 1996, New Astronomy, 1, 245
Wu, X.-Y., Hamilton, T. T., Helfand, D. J., & Wang, Q. D. 1991, ApJ, 379,

https://doi.org/10.1017/S0074180900114743 Published online by Cambridge University Press