The Astrophysical Journal, 469:L77–L80, 1996 October 1

LIMITS ON FAR-ULTRAVIOLET EMISSION FROM WARM GAS IN CLUSTERS OF GALAXIES WITH THE HOPKINS ULTRAVIOLET TELESCOPE

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Received 1996 May 2; accepted 1996 July 17

ABSTRACT

We have searched the far-UV spectra of five clusters of galaxies observed with the Hopkins Ultraviolet Telescope (HUT) for emission in the resonance lines of O VI λλ1032, 1038 and C IV λλ1548, 1551. We do not detect significant emission from either species in any of the spectra. Lieu et al. have recently proposed a warm [(5–10) × 10^5 K] component to the intracluster medium (ICM) to explain excess 0.065–0.245 keV flux present in *EUVE* and *ROSAT* observations of the Virgo cluster. If the surface brightness of this warm component follows that of the hot, X-ray–emitting gas (i.e., is centrally condensed), then our upper limit to the O VI surface brightness in M87 is inconsistent with the presence of substantial 5 × 10^5 K gas in the center of the Virgo cluster. This inconsistency may be alleviated if the central gas temperature is $\gtrsim 7.5 \times 10^5$ K. HUT limits on the O VI surface brightness of the four other clusters can provide important constraints on models of their ICM.

Subject headings: galaxies: clusters: general — ultraviolet: galaxies

1. INTRODUCTION

X-ray observations of clusters of galaxies have long revealed the presence of hot (2 × 10^7 K), low-density gas permeating many clusters (Forman & Jones 1982). Recently, Lieu et al. (1996) have reported the detection of extended, extreme-ultraviolet (EUV) emission in the Virgo cluster. The emission, observed in the 0.065–0.245 keV energy band with the *Extreme Ultraviolet Explorer* (*EUVE*), extends to a radius of some 20′ about M87, the central galaxy of the Virgo cluster. The excess is also present in archival data obtained with the *ROSAT* PSPC (Böhringer et al. 1995), which overlaps the *EUVE* wavelength band at low energies. The authors interpret this emission as evidence for a second, warm [(5–10) × 10^5 K] component to the intracluster medium (ICM).

The warm gas, with a total mass of approximately 8.9 × 10^{10} $M_\odot$, would cool at a rate of at least 340 $M_\odot$ yr^{-1}, more than 30 times the cooling-flow rate deduced from X-ray observations of the hot ICM (Stewart et al. 1984). This discrepancy has led Fabian (1996) to suggest that the apparent EUV excess is an artifact of the interstellar absorption model used in the data analysis. EUV flux is strongly attenuated by gas in our Galaxy's interstellar medium (ISM). If the Galactic absorption is slightly less than currently predicted, then an EUV excess is not required to reproduce the observed spectrum.

In a note added in proof, Lieu et al. (1996) report that *ROSAT* data of Coma and the Abell clusters 2199, 1795, and 1367 are better modeled by a two-temperature gas in which the cooler component has $T \sim 10^6$ K than by a single-temperature hot gas, indicating that warm gas may not be limited to the Virgo cluster. If a reservoir of warm gas were present in the cores of clusters of galaxies, it would emit strongly in the far-UV (FUV) resonance lines of O VI λλ1032, 1038 and C IV λλ1548, 1551 as it cools through temperatures of a few times 10^5 K (Edgar & Chevalier 1986; Voit, Donahue, & Slavin 1994). Limits on the intensity of FUV lines from clusters of galaxies can thus provide important constraints on the mass of the warm component of the ICM. To this end, we have used the Hopkins Ultraviolet Telescope (HUT) to search for FUV line emission from clusters of galaxies.

2. OBSERVATIONS AND DATA REDUCTION

Our observations were carried out with HUT on the Astro-2 mission of the space shuttle *Endeavor* in 1995 March. HUT consists of a 0.9 m, f/2 mirror that feeds a prime-focus spectrograph with a microchannel-plate intensifier and photodiode array detector. First-order sensitivity extends from 820 to 1840 Å at 0.51 Å pixel^{-1}. The resolution is about 4 Å through the spectrograph's 10″ × 56″ aperture and 7 Å through its 20″ diameter aperture. The effective area is nearly 24 cm^2 at 1032 Å. The spectrograph and telescope are described by Davidsen et al. (1992), while Kruk et al. (1995) discuss modifications, performance, and calibration for the Astro-2 mission.

Of the five clusters of galaxies, Virgo, Coma, and the Abell clusters 2199, 1795, and 1367, for which Lieu et al. (1996) find evidence of (5–10) × 10^5 K gas, all but Abell 2199 were observed with HUT on Astro-2. The Hercules cluster (Abell 2151) was also observed and is included in our sample. The observations were obtained during orbital night, minimizing the strength of the various airglow features and the scattered light from Lyα, which is quite strong during the day. Two of the targets, Coma and Hercules, were observed twice; their individual spectra were added together for our analysis. For neither Coma nor Hercules was the telescope pointed at a particular galaxy. The two Coma pointings were offset from one another by some 2ʹ.4, roughly the resolution of the model that Lieu et al. fitted to the EUV data. The M87 pointing was centered on the galaxy's center of light. Table 1 lists the observations in our sample.

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TABLE 1

TARGET SUMMARY

Name	l	b	z	$E(B-V)$[a]	AMET[b]	Time (s)	Slit[c]
Hercules	31.6	44.5	0.0369	0.015	205.8	1592	6
					277.4	1592	6
A1795	33.8	77.2	0.0616	0.000	278.8	2292	6
Coma[d]	58.1	88.0	0.0232	0.013	253.0	1748	7
					254.5	2004	7
A1367	234.8	73.0	0.0216	0.000	179.8	1928	7
M87	283.8	74.5	0.00428	0.023	286.8	954	6

[a] From Burstein & Heiles 1984.

[b] Start time of observation in hours from launch (1995:061:06:38:13 UT).

[c] Slit 6 measures 10″ × 56″; slit 7 is 20″ in diameter.

[d] The two Coma pointings were offset by approximately 2'.4.

In our analysis, models are fit to raw-counts spectra using the nonlinear curve-fitting program SPECFIT (Kriss 1994), which runs in the IRAF[1] environment and performs a χ^2 minimization. Error bars are assigned to the data assuming Poisson statistics. Emission line intensities are converted to energy units using the HUT absolute calibration, which is based on white dwarf model atmospheres and is believed accurate to about 5% (Kruk et al. 1995). Throughout this paper, line intensities are expressed in units of ergs cm^{-2} s^{-1} sr^{-1} and refer to the sum of the doublet line intensities.

To set limits on the observed O VI emission, we fit a linear continuum and three emission features, the Lyβ λ1026 airglow line and the redshifted O VI $\lambda\lambda$1032, 1038 doublet, to a segment of the raw-counts spectrum. The Lyβ line is fit with a model line profile derived from raytraces of the telescope light path kindly provided by J. Kruk. Because the O VI lines are expected to fill the aperture, the same profile is used for them as for Lyβ. The wavelength of the Lyβ line is free to vary; those of the O VI lines are tied to it assuming that the emitting gas lies at the cluster redshift. The line strengths also vary freely, except that the O VI lines are held to the 2:1 ratio expected from an optically thin plasma. The O VI line is then fixed at zero counts and the spectrum refit. If $\Delta\chi^2 > 4$ (corresponding to a 2 σ deviation for one interesting parameter, in this case the total counts in the O VI line; Avni 1976), we claim a detection and determine 1 σ error bars by raising the model line strength above the best-fit level until $\Delta\chi^2 = 1$. Otherwise, we create a "background-only" data set by subtracting the O VI component of the best-fitting model (which, though not statistically significant, is usually nonzero) from the observed spectrum. We fit a linear continuum to the background spectrum, then raise the model O VI line strength above zero until $\Delta\chi^2 = 4$ to set a 2 σ limit on the flux of the O VI line. Limits to the C IV flux are set in the same way. Figure 1 shows the HUT spectrum of the Coma cluster in the region of the redshifted O VI feature; model spectra without O VI and with the line fixed at its 2 σ upper limit are overplotted.

A more complex model is required to reproduce the spectrum of M87, which has a strong stellar component. As shown in Figure 2, the redshifted O VI line falls within the broad stellar Lyβ absorption feature. In order to estimate the stellar contribution at this wavelength, we flux-calibrate the data and model it with the synthetic spectrum, based on the stellar atmosphere models of Kurucz (1992) and Clegg & Middlemass (1987) and the evolutionary tracks of Dorman, Rood, & O'Connell (1993) and Vassiliadis & Wood (1994), originally fit to these data by Brown, Ferguson, & Davidsen (1995). The model spectrum is sampled at 10 Å resolution; we interpolate it to 0.5 Å using the spline function in the IRAF routine INTERP. Limits on the flux of the O VI doublet are then set as described above.

Our limits on the line fluxes are presented in Table 2. None of the spectra show significant FUV line emission; the relatively high O VI limit derived from the M87 spectrum reflects the greater uncertainty in the spectral continuum. Dereddened intensities are calculated assuming the values of $E(B-V)$ in Table 1 and the extinction parameterization of Cardelli, Clayton, & Mathis (1989; hereafter CCM). Though the FUV portion of the CCM extinction curve is based on an extrapolation of data obtained at longer wavelengths, it is able to reproduce the general shapes of the extinction curves of early-type stars observed with *Copernicus* (CCM) and has been

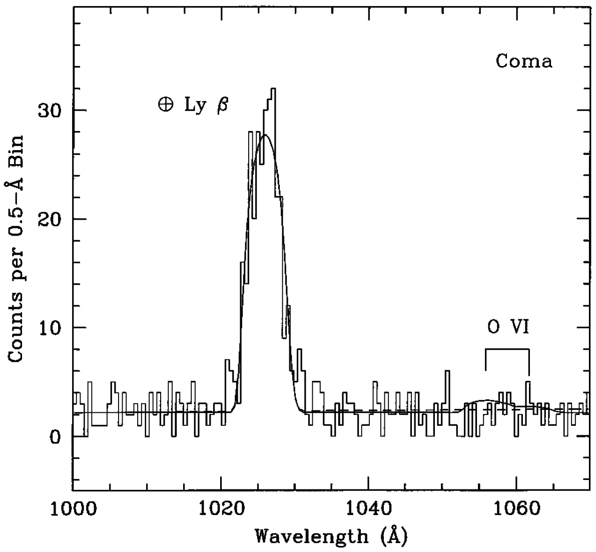

FIG. 1.—HUT spectrum of the Coma cluster, showing the region about redshifted O VI $\lambda\lambda$1032, 1038. The data are shown as a histogram and are overplotted by models including no O VI emission (*dotted line*) and O VI at our 2 σ upper limit (*solid line*).

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[1] The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.

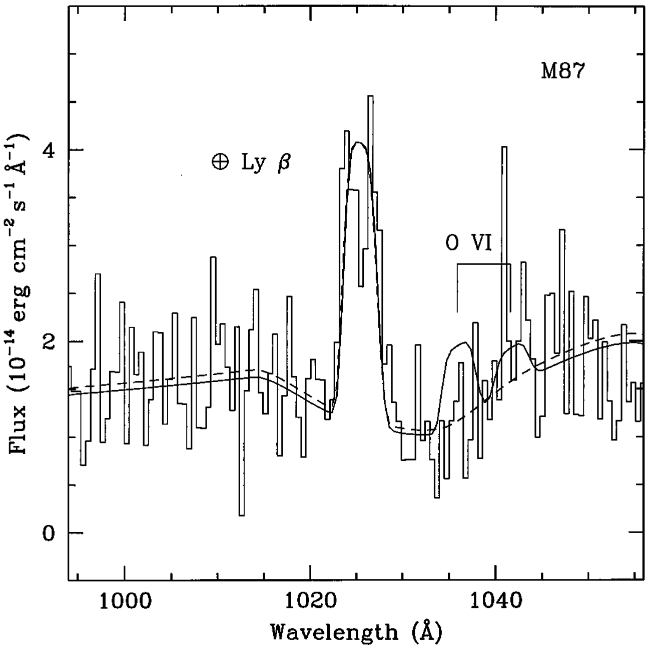

FIG. 2.—HUT spectrum of M87 in the Virgo cluster, which does not show significant O VI λλ1032, 1038 emission. The data are shown as a histogram; overplotted are models including no O VI emission (*dotted line*) and O VI at our 2 σ upper limit (*solid line*). The fit to the stellar component is from Brown et al. (1995).

used successfully to model the FUV spectra of hot stars and galaxies observed with HUT (e.g., Brown et al. 1995; Dixon, Davidsen, & Ferguson 1995). We follow Brown et al. (1995) in assuming $R_V = 3.05$ for the diffuse ISM along these lines of sight (see Buss et al. 1994); uncertainties in R_V do not greatly affect our result, as the FUV extinction $A(\lambda)$ varies slowly with R_V when $E(B - V)$ is small.

3. DISCUSSION

We do not detect significant emission from redshifted O VI λλ1032, 1038 and C IV λλ1548, 1551 in the HUT spectra of five clusters of galaxies. Are our limits consistent with the EUV emission detected in the Virgo Cluster?

Lieu et al. assume a distance to M87 of 20.6 Mpc. Fitting a two-temperature model to the combined *EUVE* and *ROSAT* data, they derive the temperature, emission integral ($EI \equiv \int n_p n_e \ dV$), and abundance of both the warm and hot components of the ICM as a function of radius. For the warm component in the central region ($r < 3'$) of the cluster, they find a temperature of $5.0^{+1.9}_{-} \times 10^5$ K, an emission integral of $3.71^{+}_{-2.09} \times 10^{64}$ cm^{-3}, and an abundance of $0.592^{+0.037}_{-0.061}$ relative to solar. (The lower bound of the temperature and the upper bound of the emission integral are unconstrained in the fit.) Using the best-fit values for each of these parameters and line emissivities estimated with the Raymond-Smith (1977) plasma code by C.-Y. Hwang, we find that the O VI flux expected from the warm gas in the central region of the Virgo cluster is 6.9×10^{-12} erg cm^{-2} s^{-1}. If we assume that the O VI flux is evenly distributed within this region, then its surface brightness is 2.9×10^{-6} erg cm^{-2} s^{-1} sr^{-1}, or 60% of our dereddened upper limit.

TABLE 2

2 σ UPPER LIMITS TO FAR-ULTRAVIOLET EMISSION LINES

	O VI λλ1032, 1038		C IV λλ1548, 1551	
NAME	Observed	Dereddened	Observed	Dereddened
Hercules..........	0.577	0.700	0.565	0.631
A1795	1.12	1.12	1.19	1.19
Coma.............	1.21	1.43	1.65	1.81
A1367	2.24	2.24	1.20	1.20
M87	3.52	4.84	3.07	3.64

NOTE.—Units are 10^{-6} erg cm^{-2} s^{-1} sr^{-1}. Dereddened intensities assume a CCM extinction curve, the $E(B - V)$ value from Table 1, and $R_V = 3.05$.

The reddening to M87 may be less than we have assumed. The value $E(B - V) = 0.023$ presented in Table 1 (Burstein & Heiles 1984) is derived from the H I map of Heiles (1975), which gives $N_{\rm H} = 3.7 \times 10^{20}$ cm^{-2} in the direction of M87. Lieu et al. (1996) have remapped the Galactic H I column density near M87 and find $N_{\rm H} \sim (1.8$–$2.1) \times 10^{20}$ cm^{-2}, which corresponds to $E(B - V) = 0.000 \pm 0.015$ according to the prescription of Burstein & Heiles (1982, 1984). Goudfrooij et al. (1994) combine deep CCD images in B, V, I, and narrow-band Hα + [N II] to derive the amount and morphology of ionized gas and dust in 56 elliptical galaxies. They find no evidence for dust in M87, save for that associated with the Hα + [N II] jet near the nucleus (Jarvis 1990), to a detection limit of $A_B \sim 0.02$, or $E(B - V) \sim 0.005$. If extinction along the line of sight to M87 is indeed negligible, then we may compare the predicted O VI surface brightness with the observed limit presented in Table 2, rather than the dereddened value.

It is likely that the emission integral of the warm gas—and thus the predicted O VI surface brightness—is not constant across the central 6′ of the cluster. Schreier, Gorenstein, & Feigelson (1982) find that the surface brightness of the hot component of the ICM, as measured with the *Einstein* HRI, falls off as $r^{-1.1}$ for $20'' < r < 4'$. At larger radii, the ratio of the EUV excess to the X-ray flux is roughly constant (R. Lieu 1996, private communication). If we assume that the warm gas in the central region of the cluster has a profile similar to that of the HRI data (and for simplicity that it is flat for $r < 20''$), then the fraction of the predicted O VI flux falling in the HUT slit rises by a factor of 5.6, to a mean surface brightness of 1.6×10^{-5} erg cm^{-2} s^{-1} sr^{-1}, more than 4 times the observed (and 3 times the dereddened) O VI limit set with HUT.

Our upper limit to the O VI flux corresponds to a cooling rate within the HUT aperture of $\dot{M} \lesssim 2.4\ M_\odot$ yr^{-1}, based on the models of Edgar & Chevalier (1986) rescaled by the abundance ($Z = 0.592\ Z_\odot$) of the warm gas. This value is consistent with the rate $\dot{M} \sim 2\ M_\odot$ yr^{-1} derived by Stewart et al. (1984) for the hot component of the ICM within ~1′ of the galactic center.

A substantial reservoir of warm gas may reside within a cluster of galaxies if its temperature is greater than we have assumed. The O VI line emissivity depends critically on the gas temperature, falling by a factor of 10 as the temperature rises from 5 to 10×10^5 K. From the observed limit to the O VI flux of M87, we derive an upper limit to the emission integral as a function of temperature. In Figure 3, we compare this limit with the best-fit value of the emission integral derived from the *EUVE* data by Lieu et al. (1996), scaled to the area of the HUT slit assuming that the EUV surface brightness (a) is constant across the inner region of the cluster, and (b) scales as the x-ray surface brightness. The value of the emission integral corresponding to case (b), $EI = 1.1 \times 10^{63}$ cm^{-3}, is higher

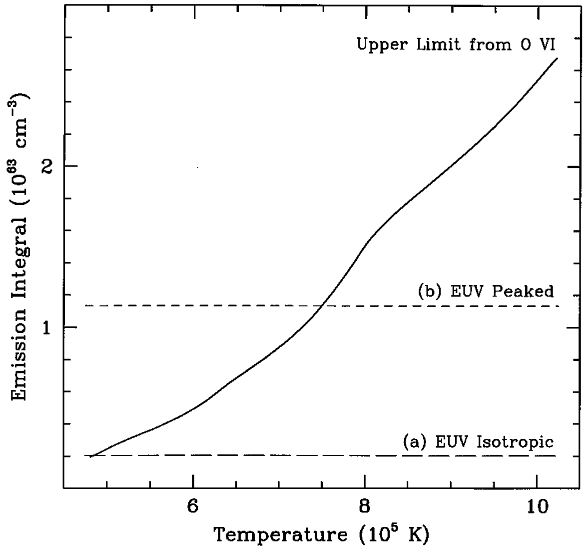

FIG. 3.—Upper limit to the emission integral ($EI \equiv \int n_p n_e \, dV$) as a function of gas temperature (*solid line*). This curve is derived from the observed (i.e., not dereddened) upper limit to the O VI flux in the HUT spectrum of M87. The horizontal lines indicate the best-fit value of the emission integral derived from the *EUVE* data for the central region ($r < 3'$) of M87 scaled to the area of the HUT slit assuming that the EUV surface brightness (a) is constant across the inner region of the cluster (*long-dashed line*), and (b) scales as the X-ray surface brightness (*short-dashed line*). For case (b), the HUT data impose a lower limit to the gas temperature of 7.5×10^5 K.

than the upper limit derived from the HUT data unless $T \gtrsim 7.5 \times 10^5$ K.

Lieu et al. (1996) report that the *ROSAT* data for Coma and the Abell clusters are best modeled by a two-temperature gas in which the cooler component has $T \sim 10^6$ K. The lower O VI emissivity expected of a 10^6 K gas may reconcile the presence of substantial warm gas with the limits set by the HUT data. As more EUV and X-ray observations of these clusters become available, the O VI limits presented in Table 2 will provide important constraints on models of their intracluster media.

4. CONCLUSIONS

We have searched the spectra of five clusters of galaxies observed with the Hopkins Ultraviolet Telescope for redshifted O VI λλ1032, 1038 and C IV λλ1548, 1551 emission. We do not detect significant emission in either feature in any of the spectra. If the surface brightness of the EUV emission in the central region ($r < 3'$) of the Virgo cluster is centrally condensed, then our upper limit to the O VI surface brightness is inconsistent with that predicted for the 5×10^5 K gas proposed by Lieu et al. (1996). This inconsistency may be alleviated if the gas temperature is $\gtrsim 7.5 \times 10^5$ K. HUT limits on the O VI surface brightness of the four other clusters can provide important constraints on models of their intracluster media.

We would like to thank J. Kruk for providing raytrace results and C.-Y. Hwang for calculating line emissivities. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration; the NASA ADS Abstract Service; and the Catalogue Service of the CDS, Strasbourg, France. We wish to acknowledge the efforts of our colleagues on the HUT team as well as the many NASA personnel who helped make the Astro-2 mission successful. The Hopkins Ultraviolet Telescope Project is supported by NASA contract NAS 5-27000 to the Johns Hopkins University. W. V. D. and M. H. acknowledge support from NASA grant NAG5-696.

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