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28. We thank K. A. Matveev, J. M. Golden, B. I. Halperin, and M. Stopa for helpful discussions and A. Adourian, M. A. Eriksson, J. Hergenrother, J. A. Katine, J. G. Lu, and D. Ralph for experimental assistance. Supported at Harvard by NSF grant NSF-DMR-95-01438, by Office of Naval Research grant N00014-95-1-0866, and in part by the Materials Research Science and Engineering Center of NSF under award DMR-94-00396 and at UCSB under grant AFOSR F 49620-94-1-0158. C.L. and C.H.C. were supported by the NSF Graduate Fellows Program; C.H.C. was also supported by the AT&T Graduate Research Program for Women.

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Diffuse Extreme-Ultraviolet Emission from the Coma Cluster: Evidence for Rapidly Cooling Gases at Submegakelvin Temperatures

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The central region of the Coma cluster of galaxies was observed in the energy band from 0.065 to 0.245 kiloelectron volts by the Deep Survey telescope aboard the Extreme Ultraviolet Explorer. A diffuse emission halo of angular diameter ~30 arc minutes was detected. The extreme-ultraviolet (EUV) emission level exceeds that expected from the x-ray temperature gas in Coma. This halo suggests the presence of two more phases in the emitting gas, one at a temperature of $\sim 2 \times 10^6$ kelvin and the other at $\sim 8 \times 10^5$ kelvin. The latter phase cools rapidly and, in steady state, would have produced cold matter with a mass of $\sim 10^{14}$ solar masses within the EUV halo. Although a similar EUV enhancement was discovered in the Virgo cluster, this detection in Coma applies to a noncooling flow system.

The Coma cluster of galaxies is a well-studied, extended x-ray source, the bright emission of which can be associated with a hot, stable, and isothermal intracluster gas (*1–3*). Here we report evidence for cooler and rapidly cooling gas components in the central region of the cluster obtained from a 36,000-s Extreme Ultraviolet Explorer (EUVE) deep survey (DS) observation in the passband from 65 to 245 eV. The axis of the DS telescope was pointed at the x-ray centroid (XRC) of Coma as determined from a Roentgen satellite (ROSAT) image in the public archive (*4*). No point source was detected at or near the XRC, but a strong and azimuthally symmetric emission halo was found with a boundary radius of angular size ~15 arc min; the background level farther out was determined and subtracted from the halo data (Fig. 1).

To understand the origin of the EUV emission, an accurate measurement of the line-of-sight galactic neutral hydrogen (HI) column density (N_H), and its spatial uniformity, is necessary. We performed dedicated HI observations of the Coma region at the radio wavelength of 21 cm with an angular resolution of 20 arc min (*5*). The resulting map indicates that the HI distribution over the entire Coma x-ray emission region is smooth. This was confirmed by an image of the same region taken at a wavelength of 100 μm (*6*), which has a resolution of several arc minutes. Within an angular distance of at least 30 arc min from Coma's XRC, we found that $N_H = 8.7 \times 10^{19}$ cm^{-2} (*7*). The 1σ uncertainty is nominally 1.0×10^{19} cm^{-2} (*8*). We assumed this value of N_H in all ensuing analyses. To model the galactic absorption, we have generalized the Morrison-McCammon code (*9*) to include the cross section of singly ionized He where necessary.

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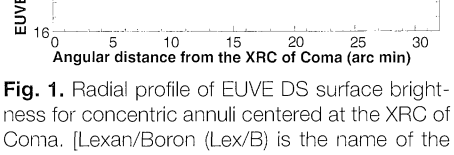

Fig. 1. Radial profile of EUVE DS surface brightness for concentric annuli centered at the XRC of Coma. [Lexan/Boron (Lex/B) is the name of the filter used in the observation.] The region between 0 and ~15 arc min corresponds to a diffuse excess that contains no point source. We determined the background level, marked by a dotted line, by averaging the data over all regions that were ≥15 arc min away from the XRC.

We investigated whether the extended nature of the EUV emission originates from the hot intracluster medium (ICM) of Coma. Owing to the high temperature of this gas, it can only be characterized by measurements in the medium-energy x-ray passband. In this regard, the data from earlier and current x-ray observatories yield consistent results. For example, the team analyzing data from the Ginga x-ray astronomy satellite (*1*) reported a temperature kT of = 8.21 ± 0.16 keV and an abundance (fraction of solar) A = 0.21 ± 0.03. We obtained similar values, $kT = 8.72^{+0.41}_{-0.37}$ and A = 0.26 ± 0.06, for the spectrum of a circular region of angular radius 15 arc min, by modeling the Gas Imaging Spectrometer 2 (GIS2) data from the Asca x-ray astronomy satellite (*10*) with the Mewe-Kaastra (MEKA) thin plasma emission code (*11*, *12*), assuming a redshift to Coma of 0.0232.

We also divided the GIS2 data spatially into smaller annuli within the same region and found no statistically significant variations in the temperature and abundance. We conclude, in agreement with previous work (*2*), that Coma's ICM is filled with an isothermal hot gas, with no evidence of a

Table 1. Observed DS Lex/B count rate for various annuli from Coma's XRC to the radius of the EUV detection limit, compared with the predicted count rates based on the use of the best parameters for the hot component as inferred from Asca GIS2 data for the corresponding annuli. All quoted errors are 1σ. c/ks, counts per kilosecond.

Annulus (arc min)	Observed (c/ks)	Predicted (c/ks)
0–3	19.4 ± 1.4	12.1 ± 0.2
3–6	38.8 ± 2.3	27.3 ± 0.3
6–9	48.9 ± 3.0	33.5 ± 0.3
9–12	44.0 ± 3.4	27.7 ± 0.3
12–15	20.0 ± 3.4	25.5 ± 0.4

cooling flow. We used the best fit GIS2 model to calculate the expected DS count rates from the hot gas and found that the predicted DS values are different from the observed count rates (Table 1). We have estimated the magnitude of the UV and x-ray leak of the DS and found that it cannot be responsible for the discrepancy (*13*).

A potential problem with the above comparison has to do with cross-calibrating Asca and EUVE data. Therefore, to further investigate the EUV component, we analyzed a ROSAT position-sensitive proportional counter (PSPC) pointed observation (*4*), which covers the passband from 0.2 to 2 keV. To obtain spatial resolution, we also sorted the PSPC events into concentric annuli, using the Coma XRC as the center. For all our PSPC spectra we focused on pulse-invariant (PI) channels 20 to 200. The extracted count rates were corrected for vignetting and dead times, and periods of high background and poor attitude solutions were excluded. We ensured data cleanliness by examining the particle background [obtained from the so-called master-veto database, which is part of the ROSAT archive (*4*)] and by selecting periods for which the level of this background would result in negligible particle contamination of the PSPC. We also found no evidence of solar-scattered radiation and long-term enhancements (*14*), because of the lack of temporal variation in the total PSPC count rates over the several days of observation.

To study the cluster emission, we subtracted from the PSPC count rates the diffuse x-ray background contribution, which is mainly due to soft x-rays at ~0.25 keV (the so-called C band). We located a suitable background region by noting from the published PSPC radial profile of the entire Coma cluster (*3*) that at distances of ~80 arc min from the XRC any residual cluster emission is negligible. We used these data to construct a diffuse background model relevant to the central region of Coma (20 arc min from the XRC) because over the entire cluster there is spatial uniformity of (i) the galactic absorbing column, as manifested in the 100-μm map (*6*), and (ii) the soft x-ray background, as revealed by the ROSAT sky survey (*15*). After extracting PSPC data from a separate pointed observation of this region, we fitted them with a two-component MEKA model. The first has $kT \sim 6$ keV, $A = 0.2$, and a foreground column of $N_H = 9 \times 10^{19}$ cm^{-2} and accounts for any residual cluster emission. The second component has $kT \sim 0.1$ keV, $A = 1.0$, and negligible foreground absorption and represents the diffuse x-ray background. This second component was subtracted from the count rates of the cluster region, including the effects of vignetting (*16*). As the diffuse background is low, small inaccuracies that may be present in this model do not affect our analysis. For example, within the innermost 3 arc min (radius) the subtraction has a 5% effect on PI channels 20 to 41, where the "soft excess" phenomenon is most apparent.

We simultaneously modeled the extracted DS and PSPC data with a single–gas component MEKA code. For direct comparison with previous results, we fixed the temperature and abundance of the emitting hot gas at the values measured by Ginga and confirmed by Asca. To avoid cross-calibration uncertainties, we fitted the model normalization constant (emission measure) to the PSPC data. Within the inner regions of the cluster where EUV emission was detected, the goodness of fit ranged from $\chi^2_{red} = 1.72$ to $\chi^2_{red} = 3.18$ for 181 degrees of freedom. No improvement in the fit was achieved when we changed the temperature and abundance within the quoted errors of the Ginga result. The main reason for the poor matches arises from the strong emission excess in the DS and PSPC C-band data (Fig. 2). When the procedure is repeated for all annuli, we find that in every annulus the observed DS count rate is higher than the model by ~4σ, that is, the DS and PSPC provided more reliable confirmation of the soft x-ray excess of Table 1. It is therefore unlikely that the phenomenon is related to systematic uncertainties in the calibration of payloads.

Could other systematic effects be re-

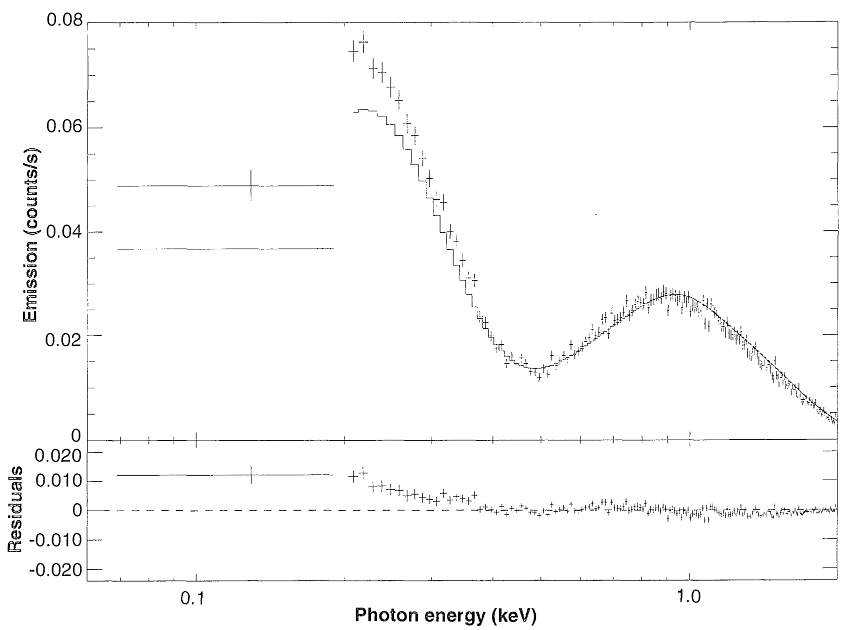

Fig. 2. Performance of the best fit MEKA single-temperature model (solid line) in a simultaneous fit to the EUVE DS and ROSAT PSPC data (the former is the first data point). The count rates correspond to those of the detected emission, and the residual is the difference between measured and model count rates. For more information see Table 2.

Table 2. Best parameters and goodness-of-fit of single-temperature (1-T), two-temperature (2-T), and three-temperature (3-T) gas component plasma models, as determined by the simultaneous fitting of the DS and PSPC data, both of which are extracted from an annulus 6 to 9 arc min from the XRC of Coma. All emission components have $A = 0.21$. A redshift to Coma of $z = 0.02316$ was assumed. The He ionization fraction corresponds to the limit of no ionized H. The quantity $\Delta\chi^2$ is the reduction in χ^2 as compared with the single-temperature model.

Model	kT_1 (keV)	kT_2 (keV)	kT_3 (keV)	N_H (10^{19} cm^{-2})	He II/(He I + He II) (%)	$\chi^2_{red}(\nu)$	$\Delta\chi^2$
1-T MEKA	8.21			8.7	0	3.18 (181)	0
1-T, variable He$^+$	8.21			8.7	93.2	1.66 (180)	277.8
1-T, variable H	8.21			6.2	0	1.61 (180)	285.4
2-T MEKA	8.21	0.182		8.7	0	1.41 (179)	323.5
2-T, variable He$^+$	8.21	0.352		8.7	88.1	1.14 (178)	373.8
2-T, variable H	8.21	0.352		6.3	0	1.14 (178)	373.1
3-T MEKA	8.21	0.326	0.071	8.7	0	1.12 (177)	376.8

sponsible for the soft excess? Emission codes like MEKA may not provide accurate estimates of the strengths of all the EUV lines. However, our knowledge of the spectrum of a gas with $kT = 8$ keV is not subject to such errors, because the EUV passband is dominated by continuum free-free emission. It has also been suggested that the soft excess is due to an overestimation of the galactic absorption (*17*). This is not remedied by application of the most recently published absorption code (*18*), which assumes a higher total absorption cross section for all wavelengths. Rather, appreciably lower absorption could occur in two ways: (i) the value of N_H is actually less than measured; or (ii) a considerable fraction of the galactic He exists in ionized form. To test these scenarios, we remodeled the DS and PSPC data by introducing two additional variables, N_H and the fraction of singly ionized He [we assumed that doubly ionized He is negligible (*19*)], while maintaining the overall ratio of He to H at 10%. The best fit results indicate that the soft excess becomes insignificant when either N_H is reduced by one-third, to about the global minimum value (*5*, *7*) or when He is ionized by ≥93%. Both are implausible scenarios. Moreover, although the goodness of fit has improved, χ^2_{red} remains large compared with unity (Table 2). We deduce that the failure of the single-temperature model must be due, at least in part, to the intrinsic emission properties of the cluster itself.

One way of countering the issue of systematic trends is to identify a bright cluster in a direction of low galactic absorption that does not show soft excess features as Coma and Virgo do (*20*, *21*). Analysis of the PSPC data of Abell 2199 (*4*) suggests that the emission of this cluster can be modeled by a single-temperature gas at $kT \sim 3$ keV, with a galactic absorption of $N_H = 9 \times 10^{19}$ cm^{-2} (*5*). There are no excess counts in the C band.

In our search for an emission model that can explain the Coma data, we attempted a two-temperature MEKA code using the N_H measured by Ginga (*22*). The best fit temperature of the new component is $kT \sim 0.18$ keV, with some variations among different annuli. The performance on one of the annuli is given in Table 2, where the χ^2 values are lower than those of a one-temperature variable absorption model, but the value of χ^2_{red} remains unacceptably high. The problem area is the residual soft excesses in the DS and in PI channels 20 to 25 of the PSPC (Fig. 3A). Further improvements to attain the parameter regime of $\chi^2_{red} \leq 1$ must involve a three-temperature model, or two temperatures with variable absorption. By applying the Ginga abundance to all emission components, we find that $\chi^2_{red} \sim 1$ for both scenarios, although the latter again requires $N_H \sim 6 \times 10^{19}$ cm^{-2} or a He ionization fraction approaching 100% (Table 2). We conclude that the use of three temperatures, which includes a very cool ($kT \sim 0.07$ keV, or $T \sim 8.12 \times 10^5$ K) component, is the only reasonable scenario within the context of thermal plasma models (Fig. 3B and Table 3).

As in the discovery of enhanced diffuse EUV emission from the Virgo cluster (*21*), a major puzzle concerning the probable existence of a multiphase ICM in Coma has to do with the cooling rate of the lower temperature components. In the three-phase model (Table 3) there is no evidence of spatial temperature gradients. We can therefore examine the dynamics of the coolest component, assuming that the ICM within a radius of 18 arc min is uniformly filled with a plasma characterized by the

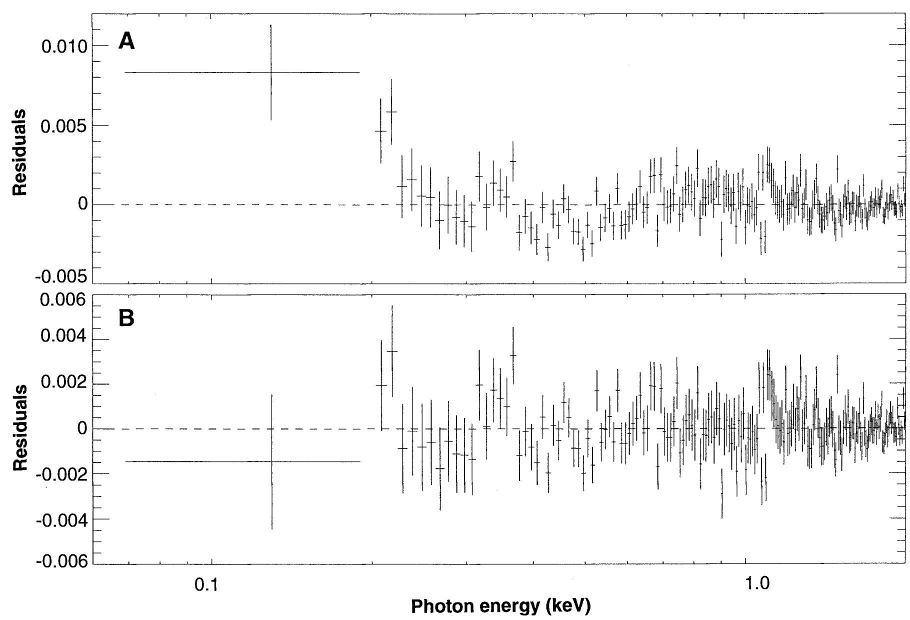

Fig. 3. Performance of the best fit MEKA multitemperature models in a simultaneous fit to the EUVE DS and ROSAT PSPC data (the former is the first data point). Residuals of the fits are plotted against energy for a (**A**) two-temperature and (**B**) a three-temperature model. For more information see Table 2.

Table 3. Best parameters and errors of a three-temperature plasma model, as obtained by the simultaneous fitting of the DS and PSPC data of Coma. All three components have $A = 0.21$, and their emission measures (EM, per cubic centimeter) are related to their respective normalization constants (Norm.) by EM = 2.3×10^{68} × Norm. × (area of annulus in square arc minutes). The hot-component temperature is $kT = 8.21$ keV. We obtained the quoted errors by using the $\chi^2 + 2.7$ criterion (*23*); $\chi^2_r(\nu)$ is the goodness-of-fit (ν denotes degrees of freedom), and χ^2_{ri} is the same for the best single- ($i = 1$) and two-temperature model ($i = 2$). Foreground absorption at $N_H = 8.7 \times 10^{19}$ cm^{-2} was applied, and a redshift to Coma of $z = 0.02316$ was assumed. For the annulus of 15 to 18 arc min only PSPC data were fitted, as no appreciable EUV emission was detected by the DS here.

Annulus (arc min)	Warm component 1		Warm component 2		Hot component norm.	$\chi^2_r(177)$	$\chi^2_{r1}(181)$	$\chi^2_{r2}(179)$
	kT (keV)	Norm.	kT (keV)	Norm.				
0–3	$(7.51^{+1.02}_{-1.17}) \times 10^{-2}$	$(7.37^{+2.71}_{-2.13}) \times 10^{-5}$	$0.33^{+0.15}_{-0.08}$	$(3.71^{+1.01}_{-0.79}) \times 10^{-5}$	$(7.36^{+0.16}_{-0.18}) \times 10^{-4}$	1.008	2.225	1.138
3–6	$(8.54^{+2.01}_{-1.35}) \times 10^{-2}$	$(3.97^{+1.14}_{-0.69}) \times 10^{-5}$	$0.442^{+0.154}_{-0.113}$	$(2.03^{+1.32}_{-0.50}) \times 10^{-5}$	$(5.93^{+0.10}_{-0.14}) \times 10^{-4}$	0.984	2.479	1.231
6–9	$(7.15^{+0.55}_{-0.63}) \times 10^{-2}$	$(3.63^{+1.05}_{-0.92}) \times 10^{-5}$	$0.326^{+0.075}_{-0.056}$	$(1.50^{+0.29}_{-0.26}) \times 10^{-5}$	$(3.99 \pm 0.05) \times 10^{-4}$	1.124	3.181	1.410
9–12	$(6.64^{+0.52}_{-0.59}) \times 10^{-2}$	$(2.41^{+0.84}_{-0.80}) \times 10^{-5}$	$0.580^{+0.124}_{-0.148}$	$(1.16^{+0.67}_{-0.49}) \times 10^{-5}$	$(2.35^{+0.06}_{-0.07}) \times 10^{-4}$	1.076	2.428	1.285
12–15	$(8.94^{+2.98}_{-1.74}) \times 10^{-2}$	$(8.72^{+3.04}_{-2.07}) \times 10^{-6}$	$0.355^{+0.189}_{-0.102}$	$(3.98^{+1.29}_{-1.18}) \times 10^{-6}$	$(1.54^{+0.25}_{-0.30}) \times 10^{-4}$	0.980	1.719	1.058
15–18	$(6.08^{+3.49}_{-3.13}) \times 10^{-2}$	$(1.34^{+13.52}_{-0.70}) \times 10^{-5}$	$0.411^{+0.145}_{-0.114}$	$(3.17^{+1.68}_{-0.95}) \times 10^{-6}$	$(9.92^{+0.20}_{-0.23}) \times 10^{-5}$	0.992	1.736	1.145

12– to 15–arc min regional best fit parameters for this component. We derive a total mass of 8.35×10^{12} $M_{\odot}$ ($M_{\odot}$ = solar mass) and a cooling time of 1.27×10^{9} years (the Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1}). The mass condensation rate to form cold matter, a quantity that does not depend on gas clumpiness, is then $\sim 6.6 \times 10^{3}$ $M_{\odot}$ per year, or $\sim 10^{14}$ $M_{\odot}$ over the age of Coma, which is phenomenal for a cluster with no signature of cooling flow. The above numbers are conservative estimates, because most of the gas is inside the annulus of 12 to 15 arc min and cools faster by virtue of its higher density. Apart from the question of the origin and destiny of the submegakelvin gas, the numbers obtained indicate that the gas may have important implications for the mass determinations in clusters. The parameters in Table 3 indicate that the two ratios of soft to hard emission measures do not scale with radial distance, which suggests the presence of cooler gases in the entire ICM of Coma. If true, the total mass budget would be significant.

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Extreme-Ultraviolet Flux from the Virgo Cluster: Further Evidence for a 500,000-Kelvin Component

Stuart Bowyer,* Michael Lampton, Richard Lieu

A surprising discovery in x-ray astronomy was that clusters of galaxies often contain vast quantities of hot (20 million kelvin) diffuse gas. Substantial diffuse extreme-ultraviolet (EUV) emission has recently been detected in the Virgo cluster of galaxies. Depending on the character of the interstellar medium in our galaxy, this emission could be either an aspect of the hot cluster gas or a previously undetected 500,000-kelvin component. Analysis of the observational data in combination with our current knowledge of the interstellar medium revealed that the EUV flux cannot be an effect of the interstellar medium. Hence, a warm cluster component appears likely.

Lieu *et al.* (*1*) studied Extreme Ultraviolet Explorer (EUVE) and Roentgen Satellite (ROSAT) data from the Virgo cluster of galaxies. Substantial EUV emission was found over a region 40 arc min in diameter centered on the giant galaxy M-87 in the center of the cluster. The ROSAT data showed a small (~20%), soft x-ray excess above that expected from the well-established high-temperature intracluster medium (ICM) (*2*). The reality of this soft x-ray excess could easily be questioned because the cutoff and the stability of the low-energy response of the ROSAT detectors are known to vary at least at the 10% level (*3*). However, for the Virgo ICM the EUV excess above that expected from the high-temperature gas is quite large (>70%) and the EUVE data seem robust. The EUVE telescopes have been recalibrated in flight every 2 months; the results of these recalibrations show the instruments to be stable to within the statistical uncertainty of the flux from the calibration sources and are better than 5% (*4*).

Lieu *et al.* (*1*) found that they could only fit the EUVE and ROSAT data from the ICM with a two-component gas, one component being the 20 million K x-ray–emitting gas and the other a warm component at 500,000 K. Although this interpretation fits the data, it is difficult to understand from a theoretical viewpoint because gas at 500,000 K is near the peak of the radiative cooling curve and will rapidly evolve to lower temperatures. This gas cannot be maintained by material cooling from the higher temperature gas; the cooling mass falls short of the required amount by more than a factor of 30. Dixon *et al.* (*5*) obtained a lower limit of 750,000 K for the temperature of this warm component from the nondetection from the Virgo cluster of emission from O VI (oxygen with five ionized electrons). At the higher temperature indicated by this observation, the cooling mass required is somewhat less but is still far greater than that which could be supplied by the x-ray gas.

Fabian (*6*) has emphasized the crucial role of absorption by the interstellar medium (ISM) of our galaxy in this interpretation. If absorption is less than expected because of the particular ionization state of this material, the EUV emission might simply be the low-energy tail of the well-established, high-temperature, x-ray–emitting ICM. It is important to establish whether the intense

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