ON THE EXTREME-ULTRAVIOLET EMISSION FROM GALAXY CLUSTERS

JOHN S. ARABADJIS AND JOEL N. BREGMAN

Department of Astronomy, University of Michigan, Ann Arbor, MI 48109-1090; jsa@astro.lsa.umich.edu, jbregman@umich.edu

Received 1998 August 1; accepted 1998 November 4

ABSTRACT

An extremely soft X-ray excess throughout galaxy clusters has been claimed as a new feature of these systems, with important physical implications. We have reexamined this feature in the five clusters for which it has been discussed, using the most recent X-ray absorption cross sections, X-ray data processing techniques, and a consistent set of H I data. For the Virgo cluster, we find that the spectrum can be fitted with a single-temperature thermal plasma and an X-ray absorption column that is not significantly different than the Galactic H I column. The results for Abell 1367, Abell 1656 (Coma), Abell 1795, and Abell 2199 are similar in that the difference between the X-ray absorption column and the Galactic H I column is less than 3 σ for He/H = 0.09, and for He/H = 0.10 only one cluster location leads to a Galactic H I column more than 3 σ above the X-ray absorption column (Coma, with one location with a 3.6 σ difference). We conclude that there is no strong evidence for the extremely soft X-ray excess in galaxy clusters.

Subject headings: galaxies: clusters: general — radiation mechanisms: nonthermal

1. INTRODUCTION

One of the surprises in the studies of galaxy clusters is that they were detected by the Extreme Ultraviolet Explorer (EUV; Lieu et al. 1996c), a satellite whose primary goal was the study of stars and gas in the local neighborhood. The EUVE has both imaging and spectroscopic capabilities that operate in the spectral range 70–760 Å (177–16.3 eV; Haisch, Bowyer, & Malina 1993). For high-latitude sight lines of low Galactic N H I (1.0 × 10^{20} cm^{-2}), the optical depth τ = 2.8 at 130 eV and τ = 1.16 at 180 eV, so 6%–30% of the emission will be unabsorbed, permitting the detection of bright soft X-ray sources. Soft X-ray emission also can be detected with the ROSAT PSPC, which has an energy response extending below 150 eV and has significantly more collecting area than the EUVE at energies of significant transmission of X-rays. At 0.13 keV (the peak sensitivity of the EUVE Lexan/boron detector), the effective area is 28 cm^2, compared with 40 cm^2 for the ROSAT PSPC. At 0.155 keV, the EUVE effective area has dropped to less than cm^2, whereas for the PSPC it is greater than 100 cm^2.

In their study of the Virgo cluster, centered on M87, Lieu et al. (1996b) were unable to successfully fit the data with a single-temperature spectral model at the ambient cluster temperature (about 2 keV) and with the X-ray absorbing column fixed at the Galactic N H I. The failure to fit the data was because of a large excess of soft residuals, indicating that there was an additional soft component. A two-temperature model led to an acceptable fit when the soft component had a temperature of about 0.05 keV, which implies that large amounts of gas at 5 × 10^5 K are present. An exciting consequence of this observation is that the cooling rate of the gas, if in a steady state, would be at least 340 M_☉ yr^{-1}, at least a factor of 30 greater than the value determined from the standard cooling flow picture of 10 M_☉ yr^{-1} (Fabian, Nulsen, & Canizares 1984). The presence of such a large amount of cooling gas has a variety of consequences, such as the mass of a low temperature component that was comparable to the virial mass of the cluster (Fabian 1996; Sarazin & Lieu 1998). There were also observable consequences, such as emission from the O VI species, which were not detected in the same clusters in which the soft component was present (Dixon, Hurwitz, & Ferguson 1996). Faced with these difficulties, another suggestion was proposed for this emission: the soft X-ray component was due to inverse Compton radiation of the cosmic microwave background by low-energy cosmic-ray electrons (Sarazin & Lieu 1998).

Since the original study of the Virgo cluster, several other clusters have been studied by the same group: Abell 1656 (Coma), Abell 1795, Abell 2199, and Abell 1367 (Lieu et al. 1996a, 1996b, 1996c; Mittaz, Lieu, & Lockman 1998; see also Table 1). In each case, the excess X-ray emission is detected at approximately the same energy, about 0.15–0.25 keV. One might expect a thermal feature to occur at the same energy in different clusters, but it seems surprising to us that a nonthermal component would always appear at the same energy.

Here we take a different approach to examining the phenomenon of the excess soft emission. Since the soft emission becomes less prominent and may disappear if lower Galactic absorption columns were possible, we ask whether it is feasible to achieve a spectral fit without the soft component and for absorption columns consistent with the Galactic N H I. Although we do not disagree with the fitting method employed by Lieu and collaborators, there has recently been a downward revision of the X-ray cross section at these energies due to improved cross sections for He I. We examine whether this change to the X-ray cross section permits an acceptable spectral fit without a soft component.

2. DATA PROCESSING AND ANALYSIS

One of the central issues in the measurement of the soft component in galaxy clusters is the correction for the absorption of X-rays by Galactic gas. A very important issue for this absorption, which has only been rectified recently, is the value for the cross section of He (Fig. 1). At energies in the 150–250 eV range, where most of the absorption occurs, He accounts for about 71% of the cross section, with hydrogen providing the remainder. The commonly used cross section of Balucinska-Church & McCammon (1992) adopted a cross section for neutral He that is based on data from Marr & West (1976). These are 18%–19%
larger than the recent determination of Yan, Sadeghpour, & Dalgarno (1998), which is similar to the determinations of Samson et al. (1994), Bizeau & Wuilleumier (1995), and Morrison & McCammon (1983, which is in turn based on data from Henke et al. 1982). By using the improved cross section for He, the total cross section at 150 eV decreases by 13%, thus causing a rise in the expected soft continuum in a single temperature fit (for fixed \( N_{\text{H}} \)).

Using the new absorption cross sections, we have addressed the issue of whether the X-ray spectra from the clusters showing a soft component can be fitted without employing a soft component. In this case, we let the value for the Galactic absorption column be a parameter that is fitted rather than fixing it. If a successful fit is discovered, as determined from an acceptable \( \chi^2 \) fit, we examine whether the fitted value for the Galactic absorption column is consistent or inconsistent with the Galactic \( N_{\text{H}} \) value.

The X-ray spectral fitting is performed on our data as discussed by Arabadjis & Bregman (1999), whereby the \textit{ROSAT} PSPC data are corrected for gain fluctuations across the image plane (through PCPICOR) and periods of time with high backgrounds are removed, which at most removes only a few percent of the data. Two concentric annuli with point sources removed were used to produce a pair of spectrally well-behaved X-ray sources for each cluster (Table 2). (In A2199 and A1795, the annuli are chosen specifically to avoid the known cooling flow regions.) The exception to this is Coma (Abell 1656), where we sought to avoid the galaxies near the center of the cluster. In that case we chose two circular regions with radii of 3′ near the center but avoided the member galaxies.

### Table 1

| Cluster | \( t \) (ks) | \( b \) (arcmin) | \( c \) (arcmin) | \( d \) (arcmin) | \( e \) (arcmin) |
|---------|--------------|------------------|------------------|------------------|------------------|
| A1367   | 234.80       | +73.03           | 3.5              | 0.0214           |                  |
| A1656   | 58.16        | +88.01           | 8.0              | 0.0231           |                  |
| A1795   | 33.81        | +77.18           | 5.1              | 0.0621           |                  |
| A2199   | 62.93        | +43.69           | 4.7              | 0.0299           |                  |
| Virgo   | 283.78       | +74.49           | 1.6,1.7          | 0.0037           |                  |

* The temperature \( T \) and redshift \( z \) are taken from White et al. 1997 and references therein, except for Virgo, whose temperature in the two source regions are determined from a \( \chi^2 \) fit.

![Comparison of neutral helium cross sections. The autoionization features near \( E \approx 60 \text{ eV} \) are shown only for the Balucinska-Church & McCammon (1992) cross sections. These are not relevant to our models, however, since the fitting range of this study is 0.14–2.0 keV.](image)

Background spectra were generally taken from annuli with widths between 2′ and 4′ and radii between 15′ and 20′, again with point sources removed.

The temperatures and redshift of each cluster were taken from White, Jones, & Forman (1997), and the metallicity assumed for each cluster was 0.3. It should be noted that other recent temperature determinations (see, e.g., White et al. 1994; Donnelly et al. 1998) are within a few tenths of a keV of our adopted values, the effect of which is minimal on the derived columns. This leaves two free parameters in each fit, the intervening column and the spectral normalization. The exception to this is Virgo, where we fitted for the temperature along with the column and normalization, and set the abundance to 0.34 (Hwang et al. 1997). The resulting temperatures, \( 1.60 \pm 0.06 \) and \( 1.67 \pm 0.11 \text{ keV} \), are consistent with the temperature profiles derived for Virgo by Nulsen & Böhringer (1995) and D'Acì, De Grandi, & Molendi (1998). The derived columns are not particularly

### Table 2

| Cluster | \( t_{\text{int}} \) (ks) | Annulus 1 | Annulus 2 | Photons 1 | Photons 2 |
|---------|-----------------|----------|-----------|-----------|-----------|
| A1367   | 18.1            | 2–8      | 8777      | 8–14      | 12070     |
| A1656   | 20.4            | 0–3       | 7508      | 0–3       | 4739      |
| A1795   | 35.1            | 3–6       | 42567     | 6–9       | 25613     |
| A2199   | 41.1            | 11–12     | 11190     | 0–3       | 11673     |
| Virgo   | 10.1            | 9–12      | 33775     | 12–15     | 31659     |

* \( t_{\text{int}} \) is the integration time for the observation.

* Two concentric source annuli (or disks, in the case of Abell 1656) were constructed for each cluster, delineated by the inner and outer radius.

* The source regions in Abell 1656 consist of two circular regions near the emission center with radii of 3′. These were chosen in order to avoid galaxies near the cluster center.

* In order to avoid bright point sources, the second source region in Abell 2199 is a circular region near the emission center with a radius of 3′.
TABLE 3
COLUMN DENSITIES TOWARD EACH CLUSTER IN THE SAMPLE

| Cluster | He/H | \(N_{\text{H,a}}\) (1)\(^b\) | \(N_{\text{H,a}}\) (2)\(^b\) | \(N_{\text{H,21 cm}}\)\(^c\) | \(N_e\) \(^d\) | \(\Delta N/e (1)\)\(^e\) | \(\Delta N/e (2)\)\(^e\) |
|---------|------|-----------------|-----------------|-----------------|----------|----------------|----------------|
| A1367   | 0.10 | 1.87 ± 0.16     | 1.65 ± 0.19     | 2.20 ± 0.110    | 0.531    | −1.70          | −2.51          |
|         | 0.09 | 2.00 ± 0.17     | 1.77 ± 0.21     | 0.90 ± 0.045    | 0.509    | −0.99          | −1.81          |
| A1656   | 0.10 | 0.781 ± 0.050   | 0.597 ± 0.071   | 0.90 ± 0.045    | 0.509    | −1.77          | −3.61          |
|         | 0.09 | 0.836 ± 0.053   | 0.639 ± 0.076   | 1.04 ± 0.052    | 0.525    | −2.25          | −2.40          |
| A1795   | 0.10 | 0.909 ± 0.026   | 0.909 ± 0.017   | 0.81 ± 0.041    | 0.744    | +0.37          | +1.07          |
|         | 0.09 | 0.964 ± 0.028   | 0.963 ± 0.019   | +1.43           | +1.97    |
| A2199   | 0.10 | 0.830 ± 0.035   | 0.877 ± 0.047   | 0.999           | 1.29     |
|         | 0.09 | 0.889 ± 0.037   | 0.939 ± 0.051   | 0.999           | 1.29     |
| Virgo   | 0.10 | 1.73 ± 0.055    | 1.59 ± 0.079    | 1.72 ± 0.086    | 0.531    | +0.10          | −1.11          |
|         | 0.09 | 1.86 ± 0.060    | 1.71 ± 0.085    | +1.34           | −0.08    |

\(^a\) In units of \(10^{20} \text{ cm}^{-2}\).
\(^b\) \(N_{\text{H,a}}\) and 1 \(\sigma\) errors toward two different source regions in each cluster.
\(^c\) \(N_{\text{H,21 cm}}\) from Hartmann & Burton 1997.
\(^d\) \(N_e\) calculated using the model of Taylor & Cordes 1993.
\(^e\) \(\Delta N/e = (N_{\text{H,a}} - N_{\text{H,21 cm}})/(\sigma_{\text{Xray}}^2 + \sigma_{\text{21 cm}}^2)^{1/2}\).

Spectral fitting was performed using XSPEC version 10 (see, e.g., Arnaud 1996), with the important change that we have put in the new cross sections for He I of Yan, Sadeghpour, & Dalgarno (1998) into the X-ray absorption routine (VPHABS). Unlike the work discussed by Lieu et al. (1996a, 1996b, 1996c), we use the ROSAT data over the energy敏感 to changes of the order of \(\delta T \sim 0.2\) K and \(\delta z \sim 0.2\), changing by less than 5%.

![Figure 2](image-url)  
**Fig. 2.—** Spectral fits and residuals for the five clusters for a helium abundance of He/H = 0.10
range 0.14–2.4 keV, but we avoid the three softest channels, for which the calibration may be unreliable (Briel, Burkert, & Pfeffermann 1989; Snowden et al. 1995).

Successful single-component fits were obtained for each of the objects (Table 3) for helium abundances of $\text{He/H}$ = 0.09 and 0.10. This range brackets most recent abundance determinations (Osterbrock, Tran, & Veilleux 1992; Baldwin et al. 1991), although Dupuis et al. (1994) found a somewhat lower value based on EUVE observations of DA stars. Our model fits show a tight correlation between the
No. 2, 1999 EXTREME UV EMISSION FROM GALAXY CLUSTERS 611

He abundance and the column density: a reduction of 10% in He/H increases the derived column by 6.5% ± 0.5%. As we discuss later, the effect is to bring the X-ray columns closer to their corresponding Galactic H I columns.

Spectral fits with He/H = 0.10 are shown with their residuals in Figure 2. In region 1 of A1656 and A1795 and region 2 of A2199, the residuals show a small systematic modulation near 0.25 keV. This is owing to a small error in the ROSAT calibration matrices, which results in a slight offset in the peak of the response function. Because the offset is in the negative direction, it does not change our conclusion: if it is not due to calibration errors, it implies either a soft X-ray deficit or a somewhat greater absorption column. As discussed above, in the case of Virgo the temperature was an additional fit parameter in the spectral modeling, and so we show confidence contours in N_{Hx} and T in Figure 3.

3. DISCUSSION AND CONCLUSIONS

The study of the Virgo cluster was the work that established the studies of soft excess emission in clusters and motivated further work, so we begin our discussion here. Our analysis leads to differences between the X-ray absorption column and the 21 cm H I column that are no greater than 1.3 σ, and the residuals are symmetric about zero (Table 3; Fig. 2). The difference between our result and that of Lieu et al. (1996b) is due primarily to the lower cross section that we used and secondarily to a lower 21 cm column density derived by Hartmann & Burton (1997). The difference between the 21 cm H I column of Hartmann & Burton (1997) and of Lieu et al. (1996b) is within the uncertainties of the two different techniques used and is probably caused by small calibration differences, as previously discussed in Arabadjis & Bregman (1999). When we use the 21 cm columns and cross sections used by Lieu et al. (1996b), we find excess soft emission as well, which nearly disappears when the intervening column in the model is allowed to be fitted. Figure 4a is a monotemperature fit to the Virgo data that uses the Lieu et al. (1996c) value N_{Hx} = 1.8 × 10^{20} cm^{-2} and fits for the cluster temperature, abundance, and metallicity. There does indeed appear to be excess emission from 0.14–0.30 keV, and the reduced \chi^2 value of the fit, \chi^2_r, is an unacceptable 1.37. The Lieu et al. (1996b) study remedied this by introducing a second (lower) temperature component that lowered \chi^2 to a marginally acceptable 1.3. Our fit (Fig. 4b), which uses the Yan et al. (1998) He I cross section and allows N_{Hx} to vary, eliminates the soft excess as well, with \chi^2_r = 1.12. We note that the X-ray column densities that we obtained are similar to those obtained by Nulsen & Böhringer (1995), who used the absorption cross sections of Morrison & McCammon (1983), which are very similar to the Yan et al. (1998) cross sections that we
Fig. 4.—Monotemperature fit to Virgo using (a) \(N_{\text{H}a} = 1.8 \times 10^{20}\) and the Balucinska-Church & McCammon (1992) He cross sections, and (b) a variable \(N_{\text{H}a}\) and the Yan et al. (1998) He cross sections. Note the excess emission on 0.14–0.30 keV in (a), which is absent in (b).

Fig. 5.—\(N_{\text{H}a}\) toward the five clusters for two different values of the assumed helium abundance.

Employed (see Fig. 1). In summary, our X-ray absorption column densities, which are similar to some other studies, are not significantly different than the 21 cm H I column density, leading us to conclude that a soft X-ray excess at energies below 0.3 keV is not a required feature of the X-ray spectrum of the Virgo cluster.

For the other four clusters, the X-ray absorption column is generally within 2.5 \(\sigma\) of the 21 cm column when \(\text{He}/\text{H} = 0.10\), and within 1.8 \(\sigma\) of the 21 cm column for \(\text{H}/\text{He} = 0.09\) (Table 3; Fig. 5). In Abell 2199, the X-ray column exceeds the 21 cm column, while for the three other clusters it is lower than the 21 cm column. However, in only one location is the X-ray absorption column more than 3 \(\sigma\) different than the 21 cm column: position 2 in the Coma cluster when using the larger He/H value of 0.10 (a 3.6 \(\sigma\) difference). We find this rather weak evidence for concluding that the X-ray absorption column is lower than the 21 cm column.

As discussed previously (Arabadjis & Bregman 1999), these findings imply that the ionized layer responsible for the pulsar dispersion measure must be very highly ionized (at least 50% of the He in the form of He III), since it cannot contribute significantly to the X-ray absorption column. However, the ionized column is consistent with that associated with a hot Galactic halo, which has been confirmed as a feature of the Galaxy by two independent groups (Pietz et al. 1998; Snowden et al. 1998).
Future work will be able to reduce the uncertainties for several of these measurements. The upcoming X-ray telescope AXAF should have an excellent calibration, and it will have greatly superior spectral resolution compared to ROSAT, so the accuracy of the fit and the resulting determination of the X-ray–absorbing column should be more accurate. Also, more accurate 21 cm measurements of the H I column will be possible with the Green Bank Telescope, which should become operational within the next year. However, a major source of uncertainty is the He/H ratio in the ISM, and unless future observations can help to decide how to handle dust corrections to photionization with improved accuracy, this uncertainty will persist.

The authors would like to thank J. Irwin, M. Sulkanen, S. Snowden, F. Lockman, D. Hartmann, and C. Sarazin for their comments and suggestions, which assisted us in this investigation. We would like to acknowledge financial support from NASA grant NAG 5-3247.

REFERENCES

Arabadjis, J. S., & Bregman, J. N. 1999, ApJ, 510, 806
Arnaud, K. A. 1996, ASP Conf. 101, Astronomical Data Analysis Software and Systems V, ed. H. R. Miller, J. R. Webb, & J. C. Noble (San Francisco: ASP), 17
Baldwin, J. A., Ferland, G. J., Martin, P. G., Corbin, M. R., Kota, S. A., Peterson, B. M., & Slettenbak, A. 1991, ApJ, 374, 580
Balucinska-Church, M., & McCammon, D. 1992, ApJ, 400, 609
Bizeau, J. M., & Wullemier, F. J. 1995, J. Electron Spectr. Rel. Phenom., 71, 205
Briel, U. G., Burkert, W., & Pfeffermann, E. 1989, Proc. SPIE 1159, 263
D'Acri, F., De Grandi, S., & Molendi, S. 1998, in Active X-Ray Sky: Results from BeppoSAX and RXTE, Nucl. Phys. B, in press
Dixon, W. V. D., Hurwitz, M., & Ferguson, H. C. 1996, ApJ, 469, L77
Donnelly, R. H., Markevitch, M., Forman, W., Jones, C., David, L. P., Churazov, E., & Gilfanov, M. 1998, ApJ, 500, 138
Dupuis, J., Vennes, S., Bowyer, S., Pradhan, A. K., & Thejll, P. 1994, BAAS, 26, 55
Fabian, A. C. 1996, Science, 271, 1244
Fabian, A. C., Nulsen, P. E. J., & Canizares, C. R. 1984, Nature, 310, 733
Haish, B., Bowyer, S., & Malina, R. F. 1993, Journal of the British Interplanet. Soc., 46, 539
Hartmann, D., & Burton, W. B. 1997, Atlas of Galactic Neutral Hydrogen (Cambridge: Cambridge Univ. Press)
Henke, B. L., Lee, P., Tanaka, T. J., Shimabukuro, R. L., & Fujikawa, B. K. 1982, At. Data Nucl. Data Tables, 27, 1
Hwang, U., Mushotzky, R. F., Loewenstein, M., Markert, T. H., Fukazawa, Y., & Matsumoto, H. 1997, ApJ, 476, 560
Lieu, R., Mittaz, J. P. D., Bowyer, S., Breen, J. O., Lockman, F. J., Murphy, E. M., & Hwang, C.-Y., 1996a, Science, 274, 1335
Lieu, R., Mittaz, J. P. D., Bowyer, S., Lockman, F. J., Hwang, C.-Y., & Schmitt, J. H. M. 1996b, ApJ, 458, L5
Marr, G. V., & West, J. B. 1976, At. Data Nucl. Data Tables, 18, 497
Mittaz, J. P. D., Lieu, R., & Lockman, F. J. 1998, ApJ, 498, L17
Morrison, R., & McCammon, D. 1983, ApJ, 270, 119
Nulsen, P. E. J., & Böringer, H. 1995, MNRAS, 274, 1093
Osterbrock, D. E., Tran, H. D., & Veilleux, S. 1992, ApJ, 389, 305
Pietz, J., Kerp, J., Kalberla, P. M. W., Burton, W. B., Hartmann, D., & Mebold, U. 1998, Astron. Astrophys. Trans., 332, 55
Samson, J. A. R., He, Z. X., Yin, L., & Haddad, G. N. 1994, J. Phys. B, 27, 887
Sarazin, C. L., & Lieu, R. 1998, ApJ, 494, L177
Snowden, S. L., Egger, R., Finkbeiner, D. P., Freyberg, M. J., & Plucinsky, P. P. 1998, ApJ, 493, 715
Snowden, S. L., Turner, T. J., George, J. M., & Yusaf, R. 1995, OGP Calibration Memo CAL/ROS/95-003
White, D. A., Jones, C., & Forman, W. 1997, MNRAS, 292, 419
White, R. E., III, Day, C. S. R., Hatsukade, I., & Hughes, J. P. 1994, ApJ, 433, 583
Yan, M., Sadeghpour, H. R., & Dalgarno, A. 1998, ApJ, 496, 1044
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674