EXTREME-ULTRAVIOLET EMISSION IN THE FORNAX CLUSTER OF GALAXIES

STUART BOWYER, ERIC KORPELA, AND THOMAS BERGHÖFER

Space Sciences Laboratory, University of California at Berkeley, Berkeley, CA 94720-7450; bowyer@ssl.berkeley.edu

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ABSTRACT

We present studies of the extreme-ultraviolet (EUV) emission in the Fornax Cluster of galaxies, a relatively nearby well-studied cluster with X-ray–emitting cluster gas and a very large radio source. We examine both the large-scale (approximately the size of the X-ray–emitting cluster gas) and the small-scale (<1') emission. We find that this cluster has large-scale diffuse EUV emission. However, at the sensitivity level of the existing Extreme Ultraviolet Explorer (EUV) data, this emission is entirely due to the low-energy tail of the X-ray–emitting gas. We have also examined small-scale structures in raw EUVE images of this cluster. We find that small-scale irregularities are present in all raw Deep Survey images as a result of small-scale detector effects. These effects can be removed by appropriate flat-fielding. After flat-fielding, the Fornax Cluster still shows a few significant regions of small-scale EUV enhancement. We find that these are emission from stars and galaxies in the field. We find that at existing levels of sensitivity, there is no excess EUV emission in the cluster on either large or small scales.

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

1. INTRODUCTION

The Fornax Cluster (Abell S0373) is a relatively poor cluster at a distance 25 Mpc. It is well studied in the X-ray, radio, and optical bands. It contains the radio galaxy Fornax A, which is well known for its giant radio lobes that extend almost a degree across the sky. The brightest optical galaxy in the group is NGC 1399, which is an E1 galaxy located near the center of the cluster. The cluster has an associated X-ray–emitting gas that has been studied by a number of investigators, most recently by Jones et al. (1997). They find that the cluster gas has a mean temperature of 1.3 keV and a heavy-element abundance of 0.6 with respect to solar. The cluster X-ray emission is ~36' in diameter, roughly centered on NGC 1399.

We studied the Fornax Cluster in the hope that it might shed light on the underlying source mechanism of the EUV emission found in some clusters of galaxies. We were particularly interested in this cluster since Berghöfer, Bowyer, & Korpela (2000a) showed that the jet in M87 may have activated the EUV emission in the Virgo Cluster. Although Fornax A is well away from the cluster center and was not in the field covered by our observation, we entertained the possibility that this radio source might be activating processes in the central part of the cluster. Throughout this Letter, we assume a Hubble constant of 50 km s⁻¹ Mpc⁻¹ and Ω₀ = 0.5.

2. DATA AND ANALYSIS

The Fornax Cluster was observed from 1998 August 29 through September 2. During this period, 104 ks of data were obtained. The cluster center was placed about 6' away from the known dead spot of the detector.

The reduction of the data was carried out with the Extreme Ultraviolet Explorer (EUV) package built in IRAF. We employed the analysis methods described in detail in Bowyer, Berghöfer, & Korpela (1999; see Berghöfer, Bowyer, & Korpela 2000b for a definitive discussion of the validity of these procedures). Briefly, corrections for dead time and telemetry limitations were applied to the data set, and a raw EUV image was produced. A flat nonphotonic background, determined from highly obscured regions at the outer most parts of the field, was subtracted from this image. We then computed the azimuthally averaged radial emission profile of the raw data centered on the cluster center. In Figure 1, we show this profile. We also show the azimuthally averaged radial profile of the telescope sensitivity map (or flat field) constructed from 788 ks of blank field observations. The flat-field profile and its statistical errors are shown as gray shaded regions. As can be seen from a comparison of these data sets, no EUV emission is detected at radii larger than 5', and the detection between 4' and 5' is marginal at best. The statistical uncertainties in the flat field are small because of the large number of counts in this data set.

We determined the EUV contribution of the low-energy tail of the X-ray–emitting cluster gas by analyzing 53,100 s of ROSAT Position Sensitive Proportional Counter (PSPC) archival data on this cluster. A reanalysis of these data using an accurate Galactic hydrogen column and appropriate interstellar absorption was necessary to obtain the correct EUV emission from the cluster, although the use of these improved parameters do not affect the previous X-ray cluster gas measurements. We used the temperature of the X-ray gas as obtained by Jones et al. (1997), and we employed the MEKAL plasma code to derive the ROSAT PSPC/EUVE Deep Survey (DS) count conversion factors for each separate radial bin. The Galactic hydrogen column employed was N(H) = 1.61 × 10²⁰ cm⁻² (Murphy, Sebach, & Lockman 2001). The interstellar medium (ISM) absorption that we employed is described in detail in Bowyer et al. (1999). This reference includes an extensive discussion of the necessity of employing an improved EUV ISM absorption cross section in the analysis of EUVE data.

We established that the ROSAT PSPC/EUVE DS count conversion factor fell between 220 (kT = 0.88 keV) and 125 (kT = 1.32 keV). We estimate the uncertainties in these values to be ±20%. Employing these values and using the azimuthally averaged X-ray emission profile derived from the PSPC hard-energy band (0.5–2.4 keV), we derived upper and lower limits for the EUV emission from the X-ray–emitting gas in the EUVE DS bandpass. In Figure 2, we show the EUV emission from the X-ray–emitting gas as shaded regions, with uncertainties in this emission indicated by the size of the shaded bin. We also show the EUV emission in the cluster as derived...
Fig. 1.—Azimuthally averaged radial EUV emission profile of the Fornax Cluster (solid line and 1 σ error bars). The azimuthally averaged radial profile of the background, or flat field, obtained from 788 ks of blank field data is shown as the gray shaded region. The 1 σ errors in this background are indicated by the size of the shaded area.

Fig. 2.—EUV emission in the Fornax Cluster as derived from the data displayed in Fig. 1 (solid line with error bars). The statistical uncertainties in the flat field and the signal are added in quadrature. The EUV emission from the X-ray gas and its uncertainties are shown as gray shaded regions. There is no evidence for excess large-scale EUV emission in the cluster.

Fig. 3.—A 20′ × 20′ map of the central portion of the Fornax Cluster showing small-scale structure in the background-subtracted data. The contour levels are −3 σ, −2 σ, 2 σ, 3 σ, and 4 σ. The largest positive deviation is coincident with the X-ray cluster gas. The point source to the southeast is the galaxy NGC 1404. The position of the source to the southwest is coincident with an unnamed star. The position of the point source to the east of the cluster center is consistent with the galaxy CGF 1-3.
examined both our 104 ks of Fornax Cluster data and a number of blank field data sets. Hardcastle (2000 and references therein) has shown that extreme care must be taken in determining the validity of features in an image that has been smoothed as described. The statistics in the smoothed image are neither Poissonian (because of the smoothing) nor Gaussian (because of the small number of counts in each cell). Hardcastle (2000) points out that one cannot simply determine the rms dispersion of an image after smoothing, multiply by $n$, add the mean, and call the resulting contour level “$n\sigma$.”

Hardcastle (2000) points out that there is no analytic solution to the problem of establishing the statistical significance of a data set after smoothing. Hardcastle describes a Monte Carlo procedure that gives valid results. A field of simulated Poisson noise with the same bin size as the true data set is convolved with a Gaussian used with these data, and the statistical uncertainty levels are derived directly from the distribution of the resulting noise. An “equivalent” 3 $\sigma$ contour is defined as the contour that includes all but 0.135% of the data. Contours of other significance levels are defined in an analogous manner.

Following these procedures, we carried out a Monte Carlo simulation of Poisson noise in an empty field to determine the expected fraction of the field exceeding various levels of significance. The results of this simulation are shown in the second column of Table 1. Given that this data set is used to define these levels, they precisely match their respective statistical level. For comparison, we also show in the third column the expected deviations (at these equivalent $\sigma$ levels) as calculated from Poisson statistics. These are clearly different, confirming the work of Hardcastle (2000). In the fourth column, we show the fraction of regions in the Fornax field with these statistical significance levels. The Fornax image shows more positive deviations than would be present by chance.

To evaluate these fluctuations further, we examined a number of blank field data sets. In the second column of Table 2, we show the fraction of the field exceeding various levels of significance in a set of 205 ks of blank field data (set 1). In this column, we list the results for the blank field data after subtraction of the mean. There are substantial regions showing statistically significant structure in this raw data set. In the third column, we show the results after subtraction of an independent set of 425 ks of blank field data (set 2) scaled in the same manner used with the cluster data. This subtraction provides a flat-fielded image of the set 1 blank field data. In the fourth column, we show the Monte Carlo simulation of smoothed Poisson noise (reproduced here from the second column of Table 1 for the convenience of the reader). The fluctuations in the flat-fielded blank field data are consistent with the Monte Carlo simulation of smoothed Poisson noise.

### Table 1

| Level | Monte Carlo Simulation | Poisson Statistics | Fornax Field |
|-------|------------------------|--------------------|--------------|
| $>4\sigma$ | 0.0003 | 0.003 | 0.003 |
| $>3\sigma$ | 0.0013 | 0.010 | 0.007 |
| $>2\sigma$ | 0.023 | 0.066 | 0.031 |
| $>1\sigma$ | 0.159 | 0.228 | 0.161 |
| $<1\sigma$ | 0.159 | 0.217 | 0.173 |
| $<-2\sigma$ | 0.023 | 0.062 | 0.024 |
| $<-3\sigma$ | 0.0013 | 0.010 | 0.0019 |

### Table 2

| Level | Set 1 | Flat-fielded Set 1* | Monte Carlo Simulation |
|-------|-------|---------------------|-----------------------|
| $>4\sigma$ | 0.00000 | 0.00000 | 0.00003 |
| $>3\sigma$ | 0.005 | 0.0010 | 0.0013 |
| $>2\sigma$ | 0.074 | 0.025 | 0.023 |
| $>1\sigma$ | 0.267 | 0.159 | 0.159 |
| $<-1\sigma$ | 0.245 | 0.162 | 0.159 |
| $<-2\sigma$ | 0.094 | 0.024 | 0.023 |
| $<-3\sigma$ | 0.025 | 0.0018 | 0.0013 |
| $<-4\sigma$ | 0.010 | 0.0007 | 0.00003 |

* After subtraction of the mean.

### 3. DISCUSSION AND CONCLUSIONS

The data displayed in Figure 1 show that the Fornax Cluster exhibits large-scale diffuse EUV emission. However, the results displayed in Figure 2 show that this emission is due entirely to the low-energy tail of the X-ray-emitting gas and that there is no detectable excess EUV flux in the central region of the cluster. The Fornax A radio source is not activating EUV emission in the central part of the cluster at the sensitivity level provided by the existing data.

The question as to what activates the production of large-scale EUV emission in some clusters of galaxies remains unanswered. A major factor limiting this inquiry is that few of the sources that have been studied in an appropriate manner have been found to exhibit this emission; hence, few clues are available as to the nature of the underlying source mechanism(s). Excess EUV emission is clearly present in the Coma Cluster (Bowyer et al. 1999; E. J. Korpeila, S. Bowyer, & T. W. Berghöfer 2001, in preparation). It is also present in the Virgo Cluster (Berghöfer et al. 2000a). Intriguingly, the character of the emission in the Virgo Cluster emission is quite different than that in the Coma Cluster. The only generalization that can be made from a study of the emission in these two clusters is that the emission is not the product of a gravitationally bound gas. Excess EUV emission has been claimed to have been detected in Abell 1795 (Mittaz, Lieu, & Lockman 1998) and Abell 2199 (Lieu, Bonamente, & Mittaz 1999). However, these authors used a theoretically derived flat field in the analysis of these clusters that is now acknowledged by all researchers to be inappropriate. An appropriate analysis of Abell 1795 and Abell 2199 (Bowyer et al. 1999) does not show excess EUV emission.

We next discuss the small-scale structure observed in the raw Fornax image. Our analysis of blank field data shows that any field in which a constant level has been subtracted from the raw data will show a substantial number of small-scale features. These will be positive or negative, or a mix, depending on the numerical value of the constant level that has been subtracted. However, a comparison of the flat-fielded blank field data in the third column of Table 2 with the true significance levels shown in the fourth column shows that the fluctuations in a correctly flat-fielded blank field image are consistent with random noise.

We now turn to the question of small-scale structure in the correctly flat-fielded Fornax image. Most of the small-scale features seen in the raw data are no longer present, consistent with our demonstration that most of this structure is due to detector effects. However, a few regions with statistically sig-
nificantly positive deviations are present even after appropriate flat-fielding has been carried out. The large-scale feature in the raw EUVE data is closely aligned with the X-ray-emitting cluster gas and is clearly due to the EUV emission of this gas. It can be eliminated by subtracting a properly scaled X-ray image. The next most significant features have widths approximately equal to the point-spread function of the DS Telescope; they are associated with known galaxies and an unnamed star and have nothing to do with intrinsic cluster emission. It is highly likely that the few remaining enhancements in this field are also due to galaxies in the Fornax Cluster or to unidentified field stars. The negative fluctuations are consistent with their being the result of chance alignments of random fluctuations in either the Fornax data set or the background data set. We conclude that there is no evidence for small-scale EUV enhancements or deficits in the Fornax Cluster. Finally, we emphasize that investigators of diffuse emission using the EUVE (or other spacecraft) should be aware of the complexities in evaluating apparent small-scale fluctuations in the raw data set.

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