OBSERVATIONS OF THE EXTENDED X-RAY SOURCES IN THE PERSEUS AND COMA CLUSTERS FROM UHURU

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ABSTRACT

The X-ray source in Perseus identified as NGC 1275 is found to have a finite angular extent of about 35 arc minutes. The improved location of the center of the emission is consistent with NGC 1275. An improved location for the center of the Coma X-ray source is consistent both with the kinematic center of the cluster and with NGC 4874. The Perseus X-ray spectrum fits a power-law index of 1.09 ± 0.07; the Coma spectrum fits either a power law of index 1.01 ± 0.10 or a thermal-bremsstrahlung spectrum with $kT = 5.3 ± 0.6$ keV. These extended sources—Coma, Perseus, and the source in the Virgo cluster—may be a new class of X-ray objects associated with active galaxies in rich clusters.

I. INTRODUCTION

The two clusters—Coma and Perseus—are among the richest nearby clusters, Coma containing about 1000 galaxies and Perseus about 500 galaxies. X-ray emission from the vicinity of both these clusters has already been reported (Meekins et al. 1971; Fritz et al. 1971; Gursky et al. 1971a, b). Using production data from the X-ray observatory Uhuru, we have refined the locations of these two sources and have found that the source in Perseus is extended.

II. X-RAY OBSERVATIONS

The observing technique of the satellite Uhuru has been described by Giacconi et al. (1971). We have analyzed 11 days of data from 1971 January during which the satellite was scanning the Coma cluster and another 11 days spread over the months from January to March during which the satellite was scanning the Perseus cluster. For each of the two sources, 8 of the 11 days of observations were selected for further analysis.

To each day's superposed data we fitted a uniform extended source by varying in turn the angular extent and the centroid for various values of the local background. The best fit was chosen as that giving the smallest $\chi^2$ value. For this process we have used only the data from the $0.5\times5^\circ$ collimator. This procedure gives us both the centroid and extent for the superposed data from each day. Other sources examined on the same days as the extended sources showed no evidence of finite size. Furthermore, we have examined the data from the satellite's star sensors and have found that many stars are seen at the same time as the extended sources and that the fit to these data to determine the rotational equation of motion of the spacecraft agrees with the

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individual star sightings to better than 1.5; we therefore conclude that the extents we have observed are not introduced by the superposition process.

Using the centroid information with the technique described by Tananbaum et al. (1971), we have been able to improve markedly the positions for the sources in Coma and Perseus. In 1950.0 coordinates the most probable locations of the center of the X-ray emitting regions are:

- Coma (2U 1257 + 28): $\alpha = 12^h 57^m 4, \delta = 28^\circ 11'$;
- Perseus (2U 0316 + 41): $\alpha = 3^h 16^m 6, \delta = 41^\circ 21'$.

Figures 1 and 2 show the size and shape of the error ellipses corresponding to the 90 percent confidence-level contours for both sources.

The formal mean weighted value for the angular extent of our sources shown in figures 1 and 2 were found to be $W_{\text{Coma}} = 36' \pm 4'$ and $W_{\text{Perseus}} = 35' \pm 3'$. The fits to our assumed uniform source were always good (see fig. 3), as values of $\chi^2$ of approximately 1 per degree of freedom imply. The values and errors for the angular extents are purely formal and are meant only to be indicators as they depend on the model chosen to fit the data—for example, uniform extended source or extended source plus point source—and on the assumed spherical symmetry. The actual values of the angular extents for the different scan angles are shown graphically in figure 4 for both the Perseus and Coma sources. The intensities on the different days, uncorrected for systematic effects, are consistent with constant intensities of $15.0 \pm 0.6$.

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**Fig. 1.—Coma X-I.** The size of the extended X-ray source, the shape and position of the 90 percent confidence-level error ellipse, in addition to the locations of the kinematic center of the cluster, NGC 4874, and NGC 4869 are shown. Although the source has not been scanned at many varied angles, we have assumed the source to be spherically symmetric. The relative probabilities that either the kinematic center, NGC 4874, or NGC 4869 is coincident with the centroid of the X-ray source are approximately the same while that for NGC 4889 is much lower. The radio emission from NGC 4874 and NGC 4869 at 408 MHz (Willson 1970) is indicated by the dashed lines.
and 44 ± 2 counts per second for the Coma and Perseus sources, respectively. For Perseus our most precise intensity determinations were made on 1971 January 20 and 21 and 1971 February 13 and 23. For these four observations the source varied by less than 5 percent from the mean. For Coma, seven precise observations of the intensity between 1971 January 4 and January 14 varied by less than 6 percent.

The sources have not been scanned at many varied angles, and hence we are unable to differentiate between several point sources and a truly extended source. For the Perseus source, the stronger one, we have tried fitting two point sources of varying relative intensities and of varying separations to the data. Solely on the basis of $\chi^2$ we were unable to eliminate this possibility (see fig. 3).

Both the Coma and Perseus clusters of galaxies are more extensive than the above reported 0.5 X-ray sources. We have therefore considered the possibility of emission from larger regions. We have found that fits to the data from the $5^\circ \times 5^\circ$ collimator agree with those from the $0.5^\circ \times 5^\circ$ collimator. Thus, there is no evidence for the existence of a more extensive region $2^\circ - 5^\circ$ in size of lower surface brightness but of total luminosity comparable to that of the central source. Our $2 \sigma$ upper limit on the contribution to the counting rate from a $1^\circ$ wide region adjacent to the central source...
Fig. 3.—Perseus X-1. The superposition data for 1971 January 22 show the best fits to an extended source (smooth curve) and to two point sources (flat-topped curve). The points represent the counting rate averaged over one superposition bin (5 arc minutes). For the two-point-source fit we found the source separation to be $20' \pm 3'$ with $\chi^2 = 47$ (for 35 degrees of freedom) while for the uniform extended source the angular diameter was $37' \pm 5'$ with $\chi^2 = 46$ (for 36 degrees of freedom). The fit to a point source gave $\chi^2 = 68$ (for 37 degrees of freedom).

Fig. 4.—The position angle (measured from north toward east) of the direction in which the source was scanned is plotted against the angular size obtained from our fitting procedure for both sources. Coma was scanned in directions differing by about $50^\circ$ while Perseus was scanned in directions differing by only about $20^\circ$. The angular sizes for the differing position angles are consistent with a constant size for each source as shown by the dashed lines.
TABLE 1

X-RAY SPECTRAL PARAMETERS

<table>
<thead>
<tr>
<th>Source</th>
<th>Source Spectrum</th>
<th>$K$</th>
<th>$E_a$ (keV)</th>
<th>$\alpha$</th>
<th>$kT$ (keV)</th>
<th>$\chi^2$ *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perseus (2U 0316 + 41)</td>
<td>Power law</td>
<td>7.5 ± 1.9</td>
<td>≤0.9</td>
<td>1.09 ± 0.07</td>
<td>...</td>
<td>13</td>
</tr>
<tr>
<td>Coma (2U 1257 + 28)</td>
<td>Power law</td>
<td>2.7 ± 0.6</td>
<td>≤1.5</td>
<td>1.01 ± 0.10</td>
<td>...</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Thermal</td>
<td>1.5 ± 0.3</td>
<td>≤1.7</td>
<td>5.3 ± 0.6</td>
<td>...</td>
<td>4</td>
</tr>
</tbody>
</table>

* For 5 degrees of freedom.

is 1.0 counts s$^{-1}$ for the source in Coma and 2.2 counts s$^{-1}$ for the source in Perseus.

To examine the spectra of the sources in the Coma and Perseus clusters we have combined the spectral data for all the days on which the sources were observed. These summed data were then fitted with a power-law spectrum

$$\frac{dF}{dE} = K \exp \left[- \left(\frac{E_a}{E}\right)^{8/3}\right] E^{-\alpha} \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$$

and a thermal-bremsstrahlung spectrum

$$\frac{dF}{dE} = K \exp \left[- \left(\frac{E_a}{E}\right)^{8/3} - \frac{E}{kT}\right] \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$$

by the technique described by Gorenstein, Gursky, and Garmire (1968). The results of this procedure are given in table 1 for the data from 2 to 10 keV. The intensities for both sources reported here are rather higher than those reported by Gursky et al. (1971a, b). This is a result of refinements to the calibration of the pulse-height analyzers. In the case of Perseus the thermal spectrum does not yield an adequate fit to the data ($\chi^2 = 91$ for 5 degrees of freedom), and in the case of Coma we cannot distinguish between the two types of spectra.

The spectral data for Perseus are consistent with the upper limit at higher energies as determined by Lewin, Clark, and Smith (1968). We were unable to compare our results with those of Hayakawa et al. (1971) for the source in Perseus, because they gave only a graph showing the detection of the source but no value for the intensity. Our spectral index for the Perseus source disagrees with that reported by Fritz et al. (1971). This is probably due to the fact that they lacked sufficient statistics to carry out a detailed spectral-fitting procedure.

III. DISCUSSION

Observations of the Perseus and Coma clusters at radio and optical wavelengths show that diffuse emission exists there. If the X-rays we observe were coming from two or more discrete sources, they would have to be located symmetrically about NGC 1275 and NGC 4874 and separated by about one-third degree. Since there is no confirming evidence at other wavelengths for such objects we feel it is appropriate to adopt the working hypothesis that the X-ray sources in the Coma and Perseus clusters are extended by ~0°.5.

The similarity between the extended emitting regions in Coma and Perseus is quite remarkable. Their common characteristics are (1) extended X-ray sources 0°.5 in size; (2) extended radio halos 0°.5 in size; (3) possible centers of activity—NGC 1275 for Perseus and NGC 4874 for Coma—as indicated by radio observations; and (4) extended optical emission.

Ryle and Windram (1967) discuss the extended halo, 3C 84B, in the Perseus cluster which they find has a diameter of ~0°.5. They also point out the peculiar radio
emission from IC 310 and NGC 1265. In Coma, Willson (1970) finds the same qualitative radio features as those we have already mentioned in connection with Perseus. He finds a radio halo 40 arc minutes in diameter centered near NGC 4874, which he suggests is the center of activity for Coma. Also NGC 4869 shows a radio tail pointed away from NGC 4874 mimicking the behavior found in Perseus. Another common feature is that the X-ray source in Perseus is nearly centered on NGC 1275—the optical and radio candidate for the center of activity—while in Coma the source is nearly centered on NGC 4874, a possible center of activity as indicated by the radio observations. These features are illustrated in figures 1 and 2.

Both Coma and Perseus have been reported to have extended optical emission. Recently Welch and Sastry (1971a) reported optical emission from an extended region in the Coma cluster. Their estimated integrated intensity is shown in figure 4 along with the X-ray and radio data for the extended sources. In Perseus extended optical emission has been reported by Arp and Bertola (1971). In figure 4 we have shown only the X-ray and radio data for Perseus, as Arp and Bertola give no estimate of the magnitude of the diffuse emission.

The X-ray source location, if known to a high enough precision, may point to a single active galaxy as the source. Or, it may show that the X-ray source is centered on the kinematic center of the cluster. For Coma the location is consistent with both, while for Perseus the source is centered on NGC 1275 and for Virgo (Kellogg et al. 1972) the source is centered on the galaxy M87. This strongly suggests, as pointed out by Kellogg et al. (1972), that the X-ray sources are produced by active galaxies but that their extent and high X-ray luminosity may result from their being located in rich clusters. The size may ultimately be related to the size of the optical or radio halo. However, the brightness distribution is not known in detail in either X-rays, radio, or visible light, so that the observations can probably be made to fit several models of the brightness distribution. Finally, we consider the spectrum. The spectrum of the Perseus source does not fit a single temperature exponential. However, it could be made to fit to a nonisothermal source with temperatures in the range of about 10 to 100 million degrees. We earlier believed that there were slight excesses at about 6 keV in our data, which might indicate iron-line emission (Kellogg et al. 1971). However, under closer investigation we found that they could be explained by possible instrumental effects.

The present data appear to be consistent with an inverse Compton model, a synchrotron model, or a hot nonisothermal gas model for the extended source in the Perseus cluster. Nonthermal mechanisms require an agent for acceleration of electrons to relativistic energies. NGC 1275, whose nucleus is thought to be the site of violent activity (Burbidge and Burbidge 1965), and NGC 4874 are likely candidates. X-ray emission can be produced by inverse Compton scattering of the microwave-background photons by the electrons producing the diffuse, presumably synchrotron, radio emission. This mechanism is contingent on the existence of the observed radio spectrum down to frequencies on the order of \( \sim 1 \text{ MHz} \). Note that this argument applies to both the Perseus source and the Coma source and that the derived value of the magnetic field is about \( 10^{-7} \text{ gauss} \). The observed spectral data are consistent with this mechanism. For Perseus the X-ray spectral index is \( 1.1 \pm 0.1 \) while the radio index is roughly 0.7 but is poorly determined (see fig. 4) and is therefore consistent with the X-ray result. For Coma the X-ray and radio spectral indices are \( 1.0 \pm 0.1 \) and \( \sim 1.2 \), respectively. Thus, the X-ray and radio spectral indices are the same, as would be required in an inverse Compton model. Note that for Coma the optical emission lies on the extrapolation of the power-law X-ray spectrum to lower frequencies (see fig. 4). Thus, if the spectrum of the electrons producing the diffuse radio source extends to low enough energies, the resulting inverse Compton radiation could extend to low enough frequencies to produce the observed diffuse optical emission.
A thermal source requires hot gas. This could come either from the intracluster medium as discussed by Gott and Gunn (1971) or from explosions in the active galaxies. The point of view that NGC 1275 is the center of activity for the Perseus cluster is disputed by Miley et al. (1972) based upon their recent detailed radio observations. They conclude that their observations indicate the existence of a dense intergalactic gas.

The three rich clusters which are closest to us—Virgo, Coma, and Perseus—are now established as extended X-ray sources with sizes of the order of several hundreds of kiloparsecs. It may be that all rich clusters are strong X-ray sources, a possibility discussed by Gursky et al. (1972), based on the fact that there appear to be additional weaker X-ray sources detected by *Uhuru* which are associated with rich clusters.

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