

X-RAY EMISSION FROM RICH CLUSTERS OF GALAXIES

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Received 1972 March 8

ABSTRACT

The *Uhuru* catalog has revealed a significant number of rich clusters associated with X-ray sources. Combined with earlier observations of X-ray emission from the Virgo, Coma, and Perseus clusters, this suggests that most, if not all, rich clusters include an X-ray emission region of large size and of net luminosity 10^{43} – 10^{44} ergs s^{-1} .

I. INTRODUCTION

Data in the 2–8-keV energy range from the X-ray observatory *Uhuru* have revealed extended X-ray emission regions in the Virgo and Coma clusters, in each case at least 0.5° in size (Kellogg *et al.* 1971a; Gursky *et al.* 1971). Analysis of more data has confirmed these results and has furthermore shown that the source coincident with NGC 1275 is also extended by about 0.5° and is centered within the Perseus cluster (Kellogg *et al.* 1971b).

These results reinforce the view that an X-ray emitting phenomenon is associated with certain clusters of galaxies (Cavaliere, Gursky, and Tucker 1971). In particular, the three objects above share the following common features:

1. Very high X-ray luminosity, in excess of 10^{44} ergs s^{-1} in the case of Coma and Perseus.
2. Very large physical size, at least 0.9 Mpc for Coma and Perseus and 0.2 Mpc for Virgo.
3. In the Virgo and Perseus clusters the centroids of the X-ray emission are close to a galaxy (M87 and NGC 1275, respectively) which is a powerful source of nonthermal radiation.
4. In both the Coma and Perseus clusters there is present rather striking radio morphology, namely, extended radio emission from single galaxies in the form of a tail, which has been interpreted as evidence for a flow of particles, perhaps akin to a solar wind, out from the central region of the cluster as has been discussed by Ryle and Windram (1968) and Willson (1970). There is also an extended radio "halo" associated with these clusters.

Furthermore, the sources are relatively intense; for example, Perseus is seen by *Uhuru* at a counting rate of ~ 40 counts s^{-1} , which is about 10 times the minimum detectable level. With the preparation of the second *Uhuru* catalog of X-ray sources (Giacconi *et al.* 1972), we searched for other, fainter examples of these objects which must be present if we are seeing a phenomenon generally associated with clusters, rather than some chance occurrence in these three objects. In fact, we find several others, including three rich Abell clusters (Abell 1958), a rich cluster in Centaurus, and at least one region (3C 129 and 3C 129.1) showing the same kind of radio morphology as do Coma and Perseus. This leads us to conclude that we are seeing phenomena common to at least a certain class of clusters, namely, the very rich ones.

II. NEW FINDINGS FROM THE UHURU CATALOG

The newly published catalog lists 125 X-ray sources. Of these, 80 are within 20° of the galactic plane and the remainder are more or less uniformly distributed in galactic latitude. The coverage is complete only near the Milky Way; at high latitude, data for only about half the sky have been analyzed for sources. For our purposes we restricted ourselves to those sources with positional errors less than 5 square degrees; this restriction eliminated 13 sources and significantly reduced the possibility of chance coincidences without biasing the study. We further restricted ourselves to sources with intensities less than that of the Perseus cluster. The stronger ones can almost in all cases be identified as galactic X-ray sources. This leaves 72, of which 40 are within 20° of the galactic plane and thus within or close to the zone of avoidance, 19 are north of -20° declination which is essentially the region searched by Abell for clusters, and 13 are south of -20° . The 72 X-ray sources, broken down into these three zones, are listed in table 1. The new candidates for cluster sources are 2U 0258+13 (Abell 401), 2U 1144+19 (Abell 1367), 2U 1706+78 (Abell 2256), 2U 1247-41 (dense cluster in Centaurus as cited by de Vaucouleurs (1956)), 2U 0447+44 (3C 129), and possibly 2U 1957+40 (Cygnus A).

The possibility that these are chance coincidences is very small. For example, the A portion of table 1, which is the region north of -20° declination excluding the Milky Way, contains 24,000 square degrees. The 19 X-ray sources in this region occupy a total area of positional uncertainty of 21 square degrees. Of the list of 111 nearest Abell clusters prepared by Rood and Sastry (1971) comprising those clusters out to distance class 3 (i.e., to about 300 Mpc), five may be X-ray sources. For four of these, the center of cluster falls within the 90 percent error box; for the fifth (A401) the cluster center is 0.2 from the edge of the 0.7 -long error box. The coordinates of the cluster centers were taken from Sastry and Rood (1971). Formally only about 0.2 coincidences would be expected on pure chance. The statistics are actually more impressive since the five sources are all of richness class 2, of which there are only 13 in the Rood-Sastry list.

TABLE 1
X-RAY SOURCES

2U Designation	X-ray Intensity (counts s ⁻¹)	Optical, Radio Object
A. Region North of -20° Declination, excluding B		
0043+32.....	8	
0258+13.....	3	Abell 401
0410+10.....	3.0	
0426-10.....	2.3	
0440+07.....	4.7	
0525-06.....	3.8	M42
1144+19.....	3.6	Abell 1367
1207+39.....	3.5	NGC 4151
1224+2.....	4.0	3C 273
1228+12.....	22	Virgo cluster
1231+7.....	6.8	
1257+28.....	12.3	Coma cluster (Abell 1656)
1420-2.....	3	
1443+43.....	3	
1642+04.....	6.7	
1706+78.....	3.2	Abell 2256
1808+50.....	5.6	
1828+81.....	2.8	
1843+67.....	4.2	

TABLE 1—*Continued*

2U Designation	X-ray Intensity (counts s ⁻¹)	Optical, Radio Object
B. Region within 20° of the Galactic Plane		
0022+63.....	10	Tycho
0143+61.....	6	
0240+44.....	3	
0316+41.....	39.3	Perseus cluster (Abell 426)
0352+30.....	20.2	
0447+44.....	6	3C 129, 3C 129.1
0449+66.....	7.7	
0757-26.....	4	
0757-53.....	3.0	
0821-42.....	8	Puppis A
0832-45.....	10	Vela X
1005-32.....	6.3	
1022-55.....	7	
1134-61.....	12	
1211-64.....	6	
1223-62.....	32	
1254-69.....	25	
1322-42.....	7.4	NGC 5128
1440-39.....	3.2	
1509-58.....	5	
1536-52.....	13	
1542-62.....	35	
1544-75.....	2.6	
1556-60.....	24	
1626-67.....	15	
1639-62.....	9	
1701-31.....	15	
1718-39.....	18	
1757-33.....	30	
1813-12.....	10	
1822-37.....	15	
1833-5.....	8	
1912-5.....	19	
1926+43.....	9.2	
1957+40.....	5.1	Cygnus A
2012+62.....	7.7	
2041+75.....	2.4	
2130+47.....	9	
2208+54.....	5	
C. Region South of -20° Declination, excluding B		
0115-73.....	19	Small Magellanic Cloud
0426-63.....	2.6	
0521-72.....	17	Large Magellanic Cloud
0532-66.....	12	Large Magellanic Cloud
0539-64.....	17	Large Magellanic Cloud
0540-69.....	18.7	Large Magellanic Cloud
0638-54.....	4.4	
1247-41.....	5.9	Dense cluster
1253-28.....	4.7	
1849-77.....	3	
1954-68.....	3.6	
2346-32.....	3.3	
2358-29.....	2.3	

Another example is 3C 129. This object is the only other clear example known of the radio morphology exhibited in the Coma and Perseus clusters as has been discussed recently by Hill and Longair (1971). This object lies in the Milky Way region which contains about 7000 square degrees and 40 X-ray sources with a total area of position uncertainty of 11 square degrees. Thus, the chance of an accidental association for this single object is about 6 percent.

We are also impressed by the large fraction of X-ray sources that are associated with clusters. In the northern zone, this is the case for five of 19 sources, or five of 17 if we exclude NGC 4151 and 3C 273 which seem to be examples of isolated galaxies as X-ray sources. It should also be noted that most of the sources listed in the B portion of table 1 must belong to our Galaxy; however, there is no way at present to distinguish them from extragalactic objects on an individual basis.

III. DISCUSSION

The candidate cluster sources are listed in table 2 along with their accepted distances, on which basis is calculated the X-ray luminosity and the physical size where possible. If one considers the Abell clusters, which include Perseus and Coma, we find that only those of richness class 2, which is the highest richness category, are sources. The average luminosity of the five objects in this category is 4×10^{44} ergs s⁻¹. There are only eight other richness class 2 clusters out to distance class 3; and of these, six are in the farthest distance class (a limit of about 300 Mpc). Even if each of these six were equal in luminosity to Coma, they would only be marginally detectable. Furthermore, as noted, the 2U catalog does not include all the available data, particularly off the Milky Way. Thus, the present data are consistent with all the clusters of richness class 2 being X-ray sources within the range of X-ray luminosities indicated (i.e., $0.5\text{--}6 \times 10^{44}$ ergs s⁻¹).

This latter statement forms the principal conclusion of this paper, namely, that there is an extended region of very high X-ray luminosity associated with the richest clusters of galaxies, and that this is a phenomenon common to most such clusters. This conclusion is supported by X-ray sources associated with rich clusters in regions outside the Abell survey; namely, 2U 1247-41 and 2U 0447+44. In the later case, we accept the

TABLE 2
CLUSTER SOURCES

2U Designation	Optical Radio Object	X-Ray Intensity ($\times 10^{-11}$) [2-10 keV] (ergs cm ⁻² s ⁻¹)	Distance* (Mpc)	X-Ray Luminosity (ergs s ⁻¹)	Diameter of Emission Region	Rich- ness Class
0258+13.....	Abell 401	5.1	300†	6×10^{44}	750 kpc	2
0313+41.....	Perseus cluster	68	73‡	4×10^{44}		2
0447+44.....	3C 129	10	80§	8×10^{43}		?
1144+19.....	Abell 1367	6.1	85‡	5×10^{43}	250 kpc	2
1228+12.....	Virgo cluster	37	15‡	1×10^{43}		1
1247-41.....	Dense cluster	10	35	1.5×10^{43}		?
1257+28.....	Coma cluster	21	91‡	2×10^{44}	900 kpc	2
1706+78.....	Abell 2256	5.4	280†	5×10^{44}		2
1957+40.....	Cygnus A	14	220‡	8×10^{44}		?

* Derived on the basis of a Hubble constant of 75 km s⁻¹ Mpc⁻¹.

† Redshift derived from Abell's (1958) redshift-magnitude relation.

‡ Allen 1964.

§ Hill and Longair 1971.

|| Redshift taken as that for NGC 4696.

view that the radio morphology is indicative of a rich cluster. The source 2U 1957+40 may be yet a third example of a cluster source, since it coincides with a rich cluster (Baade and Minkowski 1954). However, the source also coincides with Cygnus A—the most luminous example of the giant radio sources, which include NGC 5128, already seen as an X-ray source.

The data also indicate a strong dependence of X-ray luminosity on cluster richness. The only known richness class 1 cluster detected is Virgo. Its X-ray luminosity is a factor of ~ 40 below the average of the richness class 2 clusters. This also indicates that the X-ray emission is not simply proportional to the number of galaxies in the cluster since on the average there is less than a factor of 2 difference in the number of bright galaxies between richness 2 and richness 1 clusters.

There seem to be several acceptable possibilities to account for the X-ray emission. These are:

1. Thermal bremsstrahlung from a hot gas of density $\sim 10^{-3}$ atoms per cm^3 as was first discussed for the Coma cluster by Felten *et al.* (1966). The gas could have been present since the formation of the cluster, or it could be infalling from intercluster space (Gott and Gunn 1971). The gas could be heated by the motion of the galaxies (Ruderman and Spiegel 1971) or by relativistic particles emitted from active galaxies.

2. Inverse Compton by relativistic electrons against the microwave background radiation. This process was originally proposed by Felten and Morrison (1966) to account for the diffuse X-ray background as the superposition of discrete sources. The existence of extended radio halos in certain rich clusters may support this view.

These cases are appealing to the extent that they may tie together causally the X-ray emission, the radio morphology, and the active galaxies present in these clusters. However, it is also possible that the summed contribution of a small number of very luminous X-ray emitting galaxies comprises the emission. Ten objects per cluster radiating at $\sim 10^{43}$ ergs s^{-1} would be consistent with the present data.

In the view that all richness 2 clusters are X-ray sources, their space density is the order 10^{-6} Mpc^{-3} . Given their great luminosity, the integrated effect of the more distant sources of this kind comes close to accounting for the diffuse X-ray background; however, the uncertainty in their space density and luminosity precludes making a definite statement on this point.

IV. REQUIRED ADDITIONAL OBSERVATIONS

It is apparent that certain new observations can test the conclusions reached here and help to elucidate the nature of these cluster sources. As noted the 2U catalog does not include all the available data as yet. For example, Abell 1035 is in a region from which no data have yet been analyzed.

In the optical range, a consistent classification for both southern and northern clusters could add new members to this class, particularly from the region south of -20° declination. Furthermore, the same kind of classification is needed for the clusters seen in the obscured regions near the Milky Way. In particular, we cite as candidates the source 2U 1957+40 which contains the Cygnus A cluster and 2U 0447+44 which contains 3C 129.

In the radio range, the central question is: To what extent is the radio morphology exhibited by Perseus and Coma, as well as the existence of an extended halo as emphasized by Willson (1970), common to the cluster sources? Particularly in the zone of avoidance, the radio morphology may be a more positive indication of these objects than optical observations of a cluster. Overall, based on the region containing the Abell clusters, we would expect between five and 10 additional members of this class of sources to occur in other regions of the sky where we see possibly two or three (2U 0447+44, 1247-41, and 1957+40).

We wish to acknowledge discussions with Professor H. Rood of the Van Vleck Observatory regarding the contents of this paper. This work has been supported under NASA contract NAS5-11422.

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