COLUMBIA/EINSTEIN OBSERVATIONS OF EXTRAGALACTIC X-RAY SOURCES

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I would like to report on the preliminary results of our analysis of data from the first 3 months of the Columbia Astrophysics Laboratory's (CAL) observations of extragalactic objects with the imaging proportional counter (IPC) on board the Einstein Observatory. CAL has an extensive program of extragalactic astronomy planned with the Einstein Observatory including surveys of normal galaxies, radio galaxies, active galaxies, quasars and BL Lacs, and clusters of galaxies. Early results from each one of these surveys have been received and analyzed at CAL. These observations have already allowed us to look as far out to the edge of the Universe as any observer in history, and they have improved our understanding of how our own Galaxy may have evolved through time.

NORMAL GALAXIES

X-ray observations of normal galaxies should aid us in the understanding of our own Galaxy. Observations of the galaxies in the Local Group, such as the Large Magellanic Cloud discussed by Dr. Long, allow us to study the population of discrete X-ray sources in detail, as well as to examine diffuse emission associated with large-scale structures. Galaxies just outside the Local Group may also be studied in this way. For example, a 13 000 sec IPC image of M101, a normal spiral Sc galaxy, reveals the presence of three or four discrete sources associated with the beautiful spiral arm structure of the galaxy (Fig. 1). Possible diffuse or unresolved emission is also noticeable in the IPC image. In contrast to other galaxies, no strong emission is associated with the center or the nucleus of the galaxy. The total X-ray emission is comparable to that from our Galaxy, approximately 3×10^{39} erg s^{-1}. Shorter observations of the spiral galaxy NGC5866 and the irregular galaxy NGC520 have yielded positive detections of these galaxies as weak extended X-ray sources. The explosive spiral galaxies, NGC1097 and NGC4756, have both been detected as moderately strong X-ray sources, although the latter is source confused with A1631 cluster. NGC1097 is particularly interesting because Arp (1976) has obtained deep optical plates which show the operation of an ejection phenomenon evidenced by the presence of three jets. A bright X-ray source is coincident with the bright optical nucleus and is consistent with a point source. A second source, possibly aligned with a jet, is seen 10' to the northeast. Early results from observations of four other galaxies including three radio bright galaxies have yielded null results.

Table 1(a) summarizes the results from our survey of normal galaxies and radio galaxies. Columns (1) and (2) give the name and type of object observed. Column (3) gives the distance in megaparsecs or the redshift. Columns (4), (5), and (6) give the monochromatic flux at radio, optical, and X-ray frequencies, respectively. Column (7) gives the integrated 0.5-4.5 keV X-ray luminosity at the source (cosmological parameters of $q_o = 0$ and $H_o = 50$ km s^{-1} Mpc^{-1} are used). From column (8) in Table 1(a), we see that the X-ray emission is in general $\lesssim 10^{-3}$ of the optical emission. However, radio brightness does not seem to be a strong determinant of X-ray brightness. Ultimately these observations should allow us to understand and correlate the X-ray emission from normal galaxies with their structure, mass, and dynamics as well as with their radiation in other parts of the electromagnetic spectrum.

ACTIVE GALAXIES

NGC1097 may be the precursor or the remnant of an active galaxy phase through which every galaxy goes. X-ray studies of active galaxies can improve our understanding of the evolution of galaxies. Several types of active galaxies including Seyferts, BL Lacs, and quasars were known to be X-ray emitters before the launch of the Einstein Observatory. We have now confirmed that active galaxies are indeed prodigious sources of X-ray emission. Every Seyfert galaxy (generally a spiral galaxy with a bright nucleus) or N-type galaxy (a radio bright Seyfert) examined thus far has shown itself to be a strong X-ray emitter. The source 3C109 is an extremely distant N-type galaxy. It is a strong radio and optical source. It is notable that the emission from 3C109 recorded by the IPC on March 8 is highly absorbed below 1 keV, unlike that from other active galaxies. Its luminosity, 1.7×10^{45} ergs s^{-1}, places it well within the quasar class, thus linking N-galaxies to quasars. X Comae, a type I Seyfert which is believed once to have had a quasar-like appearance (Bond and Sargent 1973), was detected strongly in a 200-s observation of the Coma cluster field on January 6. The compact Zwicky galaxy, VII Zw674, was discovered serendipitously in the 3C351 field. Its optical spectrum is similar to spectra of other normal galaxies, devoid of strong emission lines. Further observations are required to confirm the suggested identification and to understand the nature of this optically "inactive" source. Finally, the N-type galaxy RN73 was also detected as an X-ray source.

These results are summarized in Table 1(b). It can be seen from the summary table that the ratios of the X-ray to optical luminosities of these active galaxies are all several hundred times higher than those for normal galaxies. We note the similarity in their multifrequency spectra (Fig. 2). It should be emphasized, however, that since most of these galaxies vary significantly from observation to observation, simultaneous wide-band coverage of each source is important.

This is essentially what we achieved with the early April observations of the quasar 3C351 in cooperation with O'Dell (Fig. 3). Simultaneous radio observations were not available, but 3C351 is not known to be a radio variable. The 3C351 field shown in Figure 4 is extremely interesting. During our first observation of this source on January 6, the IPC image showed the presence of three strong sources, one centered $\lesssim 0.5'$ away from 3C351 and two serendipitous sources. One of the two is the compact Zwicky galaxy previously noted. The other is not a catalogued source but has since been identified as the 18th mag Seyfert galaxy. The first observation also detected a weak fourth source, 3' to the northwest of 3C351. This source is now suspected to be the quasar candidate KP1703.5+609, discussed by Sramek and Weedman (1978). 3C351 is additionally interesting because Hinzen and Scott (1978) had proposed that, along with other asymmetrical radio quasars, it may be used to probe the presence of surrounding cluster emission. The 4600 sec of summed IPC data provide marginal evidence for diffuse emission surrounding 3C351. Confirmation of the association of quasars with clusters of galaxies at large redshifts would be an important piece of evidence supporting the cosmological nature of quasar redshifts. We plan to study this region in greater depth.

Five other quasars and BL Lacs have been examined with the IPC, and five have been found to emit X-rays. The object 0237-23 is a high redshift ($z = 2.26$) quasar with multiple absorption redshift systems. At its cosmological distance, it has a measured 0.5-4.5 keV luminosity of more than 10^{47} ergs s^{-1}. The first 6000 sec of data received thus far have been searched for the existence of intervening clusters of galaxies which may be responsible for the rich absorption line systems. No evidence for such clusters has been found although the deeper pointings that are planned may yet reveal their presence. The field containing Ton 256 and NAB1612 was examined in a short 1300-sec observation. Ton 256 was found to be a strong X-ray quasar and NAB1612 to be a weak X-ray quasar. The BL Lac object A00235+164 was detected as a weak X-ray source in a short pointing. This interesting object is one of the most violently variable of all active galaxies. It had undergone a large upward transition in November 1975 and most recently in February 1979. Unfortunately, we were unable to observe this object during its violent outburst.

Table 1(c) summarizes our results for the quasars and BL Lacs in our survey. The table shows that quasars and BL Lacs, like other active galaxies, emit nearly as much radiation in the X-ray regime as in the optical. All types of active galaxies exhibit similar X-ray to optical luminosities, approximately 0.3. Their multifrequency spectra demonstrate the close connection between optical and X-ray behavior but reveal no obvious relationship with the radio behavior (Fig. 5). Multiband simultaneous observations are required to decide the true relationship between various segments of the total electromagnetic output. Such spectral observations in addition to detailed time studies can serve to test models of possible energy sources which can generate as much as 10^8 times the power of our own Galaxy.

Thus we see that galaxies exhibiting a wide variety of optical and radio behavior also exhibit a diversity of X-ray behavior, with X-ray luminosities ranging from 10^{39} to 10^{47} ergs s^{-1}. They may, however, all be linked in a common evolutionary scheme as suggested, for example, by X-ray observations of the inactive normal spiral galaxy M101, the explosive "normal" galaxy NGC1097, the N-galaxy 3C109, and quasars and BL Lacs such as 3C351 and 0109+22.

CLUSTERS OF GALAXIES

Another way in which to study the evolution of galaxies is to examine the behavior of normal and active galaxies, and possibly quasars, in clusters of galaxies. A majority of galaxies are believed to exist in cluster associations, and if quasars are really cosmological, they should be found in distant clusters and may, moreover, be the power source behind some of the cluster emission.

The existence of clusters of galaxies as X-ray sources was well established even before the launch of the Einstein Observatory. The discovery of strong iron line emission established the predominantly thermal nature of their emission. Modulation collimator observations were able to identify X-ray centroids with dominant cD galaxies in BM type I clusters (Schwartz et al. 1979). Careful statistical analysis of a large sample of 40-50 clusters led several authors including Jones and Forman (1978) to propose positive correlations in the X-ray emission with cluster richness or central galaxy density, and with other aspects of cluster morphology and cluster dynamics. However, much uncertainty remains concerning the exact nature of the emission mechanism and the role of cluster gas in the evolution of galaxies and the Universe.

Early results from CAL's cluster survey have already improved our understanding of clusters of galaxies. The Einstein IPC has been used to study the arc-minute morphology of several of the brighter X-ray clusters in several different "colors." One of the first clusters examined by us in detail was the distant, rich cluster A2142. A2142 is one of the most intrinsically luminous of cluster X-ray sources. At a measured redshift of $z = 0.090$, the 2-10 keV X-ray luminosity is 3-6 $\times 10^{45}$ ergs s^{-1}, as measured by Uhuru, Ariel V, and OSO 8. We observed the cluster for 5500 sec on January 30, 1979.

From the IPC image (Figures 6a and 6b), we see that the distribution of X-rays from A2142 is sharply peaked around a central point less than 20" from the optical center of the cluster. This is 3' south of the head-tail radio galaxy mapped by Harris et al. (1977). The distribution of X-rays is not spherically symmetric but elongated along the northwest-southeast direction with a half peak projected radius of 1.6' = 0.25 Mpc. The half peak projected radius in the orthogonal direction is 1.0'. The southeast extension is evident in the 610 MHz map by Harris et al., although several other bright radio sources observed by them are not bright in the X-ray regime. Examination of the X-ray map shows that there is a distinct secondary peak 5' northeast of the main peak. This source, consistent with a point source, contains about 8 percent of the total cluster flux. This secondary peak has no optical counterpart brighter than 16th mag on the Palomar plates. The possibility exists that this is a foreground object, but the high galactic latitude of 50 degrees makes this unlikely. The source, however, may be a field galaxy similar to the Seyfert galaxy discovered in the southeast corner of this IPC field. Our search did not reveal evidence for an extended halo, a possible signature of massive gas clouds, that Forman et al. (1978) had suggested. However, the presence of a low luminosity halo beyond the 10', 1 percent level radius cannot now be ruled out. A more detailed quantitative estimate of the flux contained in this halo will have to await the receipt of the remaining half of the planned observation, and a careful comparison of off-target versus on-target rates.

The importance of discrete source emission is better seen in CAL's observation of A539, a nearby, rich cluster previously detected by Uhuru. The IPC image of this irregular cluster, shown in Figures 7a and 7b, reveals the presence of several discrete components. Source (a) is identified with a 15.1 mag double galaxy in Zwicky's catalog which is close to the optical center of the clusters. Source (b) is identified with another catalogued galaxy. Source (c) is unidentified and does not correspond to any catalogued source. With receipt of the remaining 75 percent of the data, other discrete sources of emission may be identified in this nearby cluster.

In sharp contrast to these two images, early results from our planned detailed survey of the Coma cluster show that the X-ray morphology is dramatically different for this rich nearby cluster. An IPC observation of the center of the Coma cluster shows the X-ray distribution to be remarkably smooth overall and flat in the region between the dominant binary galaxies NGC4874 and NGC4889 (Fig. 8). From this and two other shorter pointings near the edge of Coma, we calculate that diffuse emission accounts for more than 99 percent of the flux from this cluster. Marginal detection of emission from discrete sources associated with galaxies at the edge of the cluster has been obtained. NGC4839, a possible cD galaxy discussed by Bahcall (1977), emits X-rays at the level of 10^{41} ergs s^{-1}. Mkn 059, an emission-line galaxy member of the cluster, is also found to emit X-rays at this level, a few times 10^{-4} of the total cluster emission. Receipt of the remaining 80 percent of the planned IPC observation should decide exactly how much discrete galactic emission may contribute to the total cluster emission. It will also aid us in mapping possible halo emission from the cluster. A detailed pointing with the high resolution imager (HRI) will allow us to study the arc-second structure of the central 25' of the cluster.

In addition to the detailed studies of nearby clusters, CAL also plans to survey a large number of randomly selected clusters. A significant number of clusters should also be detected in a number of medium deep survey fields. Table 2 summarizes our results for the first 13 clusters surveyed. Column (1) gives the name of the object. Column (2) gives the Abell (1958) distance class code and the measured redshift. Column (3) gives the Abell richness class code, which is a rough measure of the number of galaxies in the cluster. Columns (4) and (5) give the Bautz-Morgan and Rood-Sastry classifications for cluster morphology. Column (6) gives the raw counts detected per 1000 sec of IPC observation. Column (7) gives the 0.2-3 keV source luminosity, and the last column (8) gives the estimated half peak radial size of each cluster. All clusters richer than class 0 and closer than distance class 5 have been detected as X-ray sources, including A1631, SC1251, A2089, and A2142. A variety of Bautz-Morgan and Rood-Sastry morphology is represented. It can be seen that a wide range of intrinsic cluster luminosities can now be surveyed by Einstein. Furthermore, clusters as distant as distance class 6, such as A348, have a good chance of being detected in short, approximately 1000-sec observations. For some of the nearby clusters, short observations may also permit a determination of the surface brightness distribution. For example, we have been able to map the distribution of A2079 in a 2500-sec observation and compare it with A539 and A2142 (Fig. 9). Thus far, the X-ray core size, which measures the distribution of hot gas, appears to be comparable to the galaxy core size of 0.25 Mpc determined by Bahcall (1977). Further observations and analysis can help us determine whether they differ, and if so, how and for what types of clusters. In addition, X-ray energy or "color" information available from IPC observations can help us decide how the temperature of the hot gas varies as a function of location in the cluster. These observations, carried out to large redshifts, should improve our understanding of how clusters form and how the gas and the galaxies evolve in these clusters.

COSMOLOGY

The study of individual active galaxies and clusters of galaxies will help us understand their underlying emission mechanism and source of energy, but we have only just begun to tackle the more interesting cosmological questions which their study may help solve. Construction of accurate X-ray luminosity functions for active galaxies and clusters of galaxies from the large number expected to be detected with the Einstein Observatory should permit significant tests of cosmological models. The discovery of quasars as prodigious X-ray sources has already improved our understanding of the diffuse cosmic X-ray background. If all quasars emit X-rays at a level comparable to their optical emission and if the optical count of quasars is valid to the 21st mag (e.g., Bohuski and Weedman 1979), they may account for a large portion of the observed diffuse cosmic X-ray background, and one need not invoke the suggestion that a large amount of hot gas, sufficient to close the Universe, is present. The open expanding Universe is still favored. Direct measurement of the Big Bang expansion parameters is in principle possible through the study of distant quasars and clusters of galaxies. Unfortunately, quasars are not very good standard candles due to large differences in their intrinsic luminosities. Deep X-ray observations should lead to discovery of clusters more distant than those surveyed by Abell and others. Core radii of distant clusters may be used as standard rules in cosmological tests of the deceleration parameter out to a redshift $z \sim 1$. The maximum total X-ray cluster luminosity (approximately 3×10^{45} ergs s^{-1}) may serve as a standard candle. Schwartz (1976) has also suggested that counts of X-ray clusters of galaxies may be used to extract cosmological information. It is clear then that the Einstein Observatory has opened a new and important window onto the edge of the Universe, permitting us to view events which occurred near the very beginning of time. These studies should increase our understanding of the Universe.

We express our appreciation to the entire group whose efforts realized the success of the Einstein Observatory. This work was supported by the National Aeronautics and Space Administration under contract NAS8-30753. This paper is Columbia Astrophysics Laboratory Contribution No. 180.

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TABLE 1. SUMMARY OF COLUMBIA/EINSTEIN OBSERVATIONS OF NORMAL AND ACTIVE X-RAY GALAXIES

Name (1)	Type (2)	Distance (Mpc) (3)	Distance z (3)	Radio Flux: 1.4 GHz (Jy) (4)	Optical Flux: 548 THz (mJy) (5)	X-Ray Flux: 1 keV (μJy) (6)	X-Ray Luminosity:* 0.5–4.5 keV (ergs s^{-1}) (7)	L_x/L_o (8)
(a) Normal Galaxies and Radio Galaxies								
M101	Sc	7.2	...	0.74	2700	0.26	3×10^{39}	4×10^{-5}
NGC5866	SO	18	...	0.016	76	0.1	2×10^{40}	7×10^{-4}
NGC520	Ir II	45	...	0.25	36	~0.1	1×10^{41}	1×10^{-3}
NGC5101	SBO_3	...	...	...	58	~0.1	...	5×10^{-4}
NGC1097	SBb	25	...	0.54	210	0.25	1×10^{41}	7×10^{-4}
NGC4756	SO	...	...	0.1	18	≲0.1	...	$<2 \times 10^{-3}$
3C296	Rad/DB	142	...	4.32	48	<0.2	$<9 \times 10^{40}$	$<1 \times 10^{-3}$
3C315	Rad	650	...	3.70	0.7	<0.2	$<2 \times 10^{43}$	<0.04
PKS0349-27	Rad	1458	...	~5.0	0.7	<0.2	$<7 \times 10^{43}$	<0.04
(b) Seyferts and N Galaxies								
3C109	N	...	0.306	7.0	1.6	0.8	1.7×10^{45}	0.32
X Comae	Sy I	...	0.092	...	1(V)	1.0	8×10^{43}	0.37
VII Zw674	Comp	...	...	...	0.6	0.2	...	0.15
RN73	N	...	0.047	...	0.36	0.14	5×10^{42}	0.25
(c) Quasars and BL Lacs								
109+22	BL	...	...	0.67	1.3	0.14	...	0.04
A00235+164	BL(V)	...	0.853	2.61	0.5	0.3	8×10^{45}	~0.3
0237-23	QSO	...	2.263	7.0	0.80	0.18	1.4×10^{47}	0.45
Ton 256	QSO	...	0.131	0.021	2.5	0.97	3.4×10^{44}	0.30
NAB1612	QSO	...	0.395	...	0.44	0.15	3×10^{44}	0.14
3C351	QSO	...	0.371	3.14	1.68	0.17	9×10^{44}	0.13
KP1703.5+60.9	QSO	...	1.98	...	0.36	0.03	2.5×10^{46}	0.26

*At the source, $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$.

TABLE 2. SUMMARY OF COLUMBIA/EINSTEIN OBSERVATIONS OF CLUSTERS OF GALAXIES

Name (1)	Distance (2): Abell Class	Distance (2): z	Abell Richness Class (3)	Morphological Type: Bautz–Morgan (4)	Morphological Type: Rood–Sastry (5)	E [counts $(1000\ s)^{-1}$] (6)	X-Ray Luminosity:* 0.2–3 keV (ergs s^{-1}) (7)	X-Ray Size (′) (8)
A348	6	0.274	1	II–III	...	23	4.7×10^{44}	<1
A351	5	...	0	...	...	<27	$<7 \times 10^{43}$	...
A358	3	0.052	0	...	C	<100	$<4 \times 10^{43}$	...
A539	2	0.028	1	III	F	870	2.4×10^{44}	5
A1631	3	0.034	0	I	...	70	3×10^{43}	3
SC1251	3	0.056	0	...	cD	62	1×10^{43}	<2
A1656	1	0.023	2	II	B	...	$\sim 6 \times 10^{44}$	12.7
A2079	3	0.059	1	II–III	cD	260	1×10^{44}	2.5
A2089	4	0.070	1	II	...	9	6×10^{42}	<2
A2142	4	0.090	2	II	...	1750	1.8×10^{44}	1.5
A2160	6	0.271	1	III	...	<100	$<1 \times 10^{45}$	...
A2162	1	...	0	II–III	I	100	1×10^{43}	10
A2165	6	...	0	...	...	<40	$<2 \times 10^{44}$	...

*At the source, $H_0 = 50\ km\ s^{-1}\ Mpc^{-1}$, $q_0 = 0$.

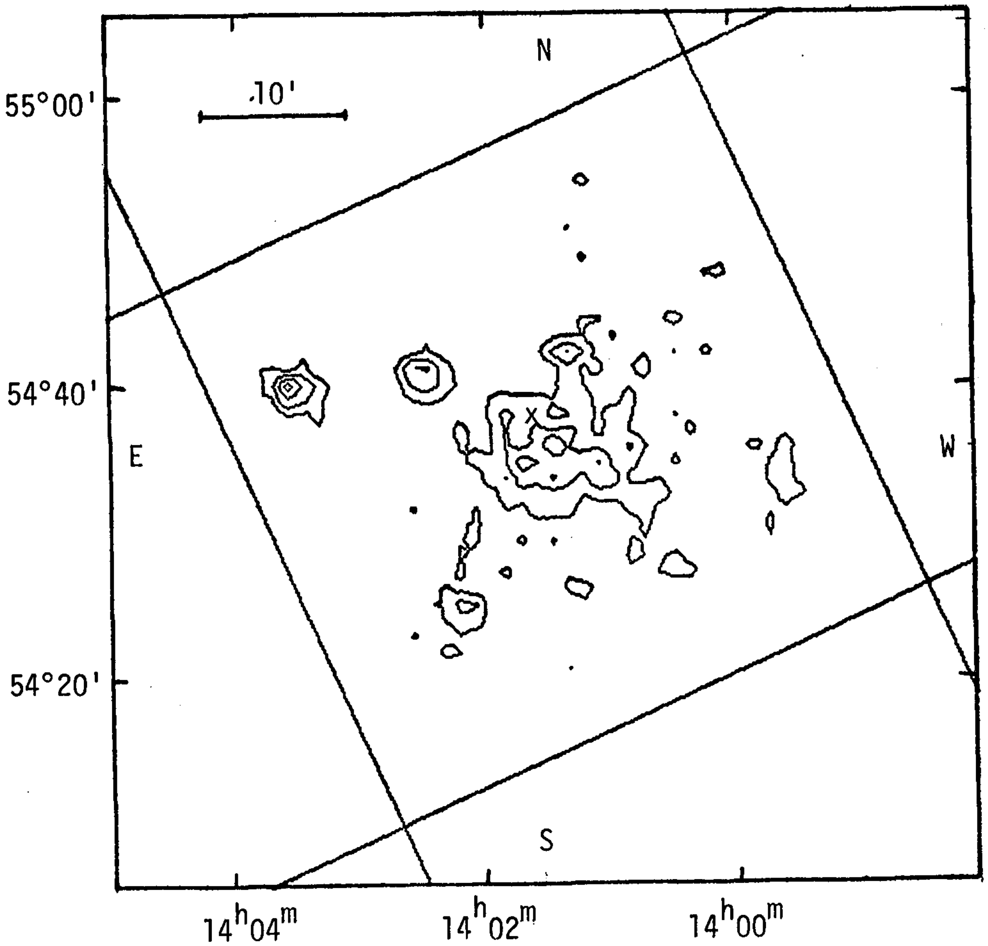


Figure 1. A 13000-sec IPC image of M101. The cross (X) marks the center of NGC5457. The four contour levels are 22, 29, 38, 49 counts per 64" × 64" cell. The intersecting lines indicate the location of the shadows of the counter support structure.

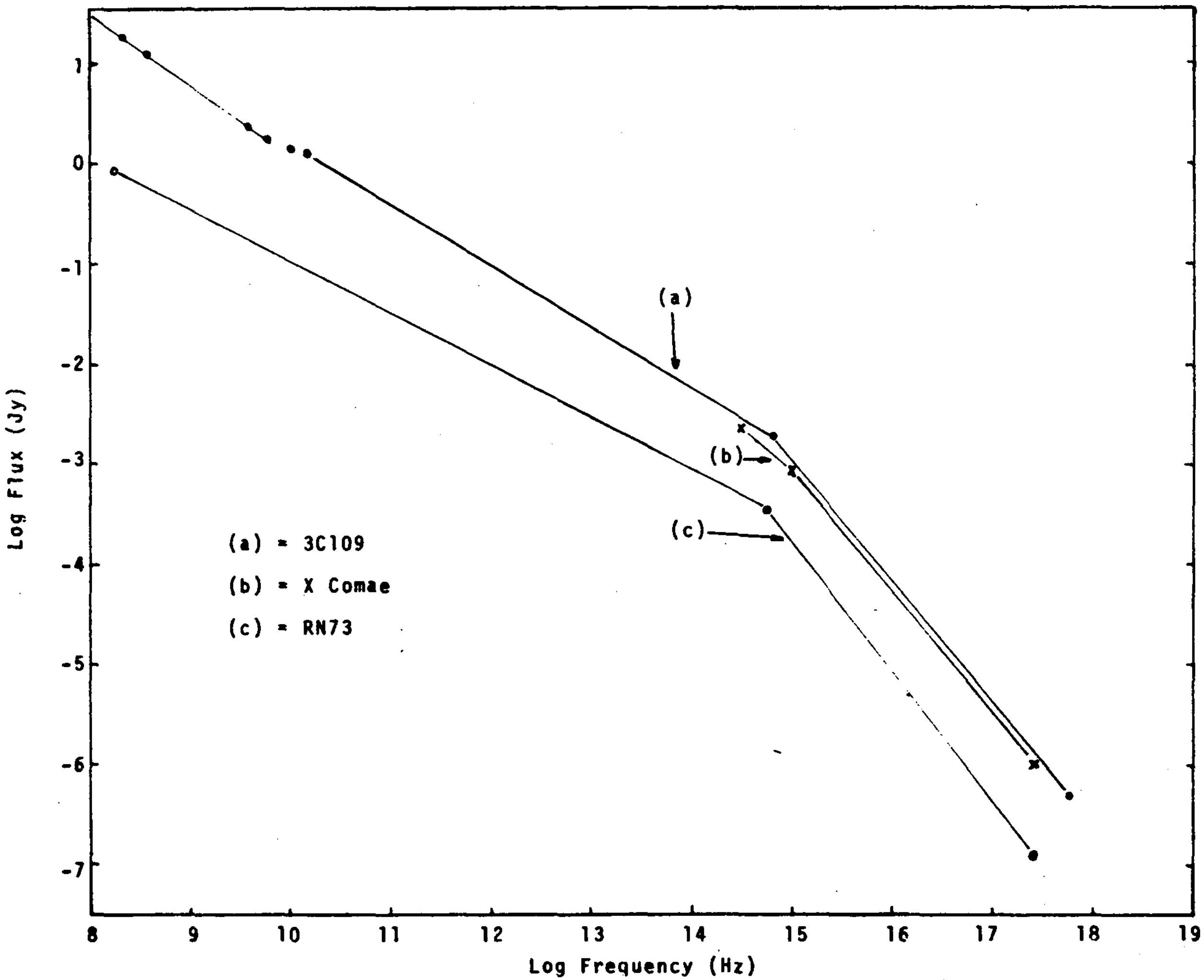


Figure 2. Multifrequency spectra of 3C109, X Comae, and RN73. Lines connecting symbols do not represent real physical relationships but are drawn to lead the eye.

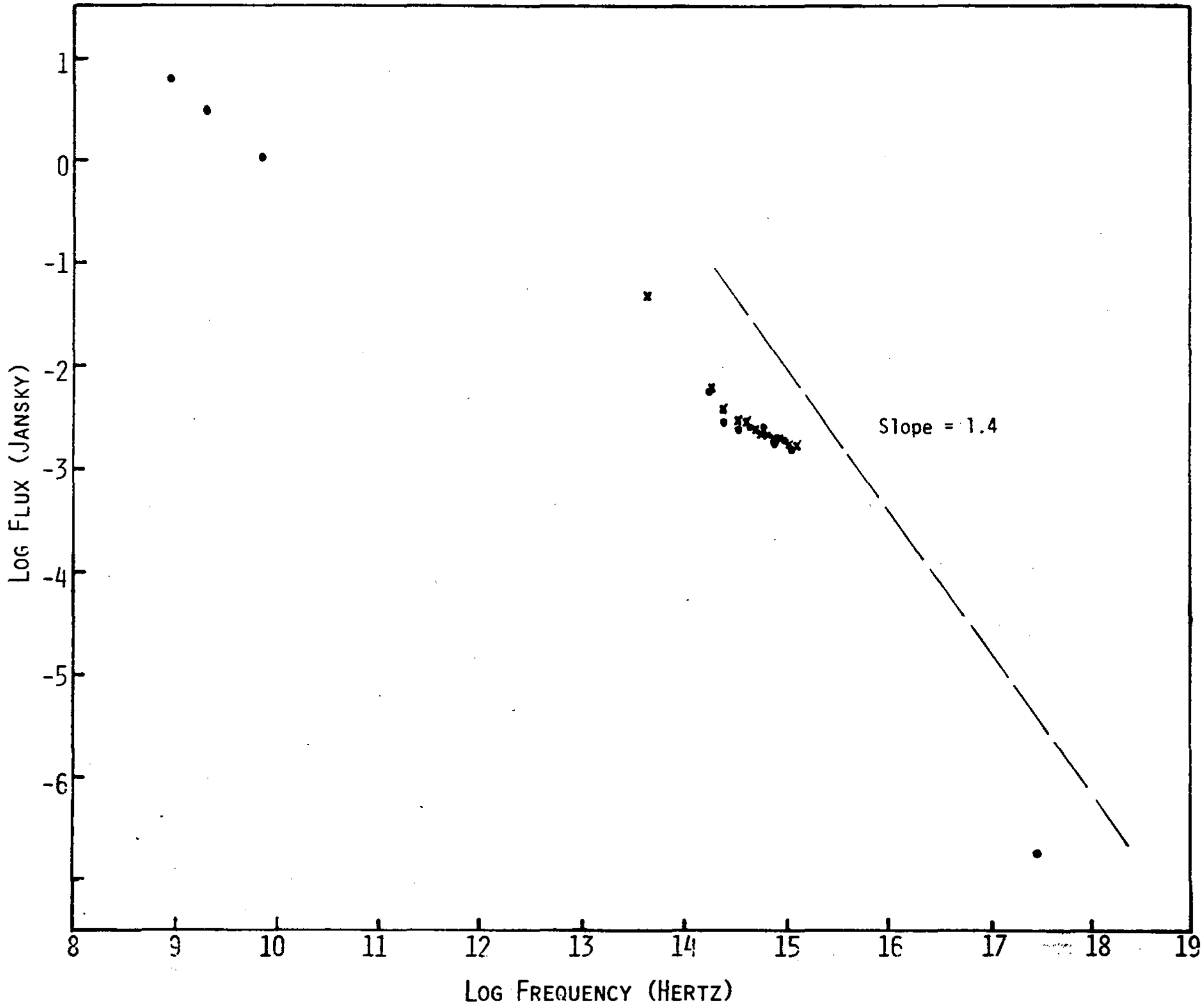
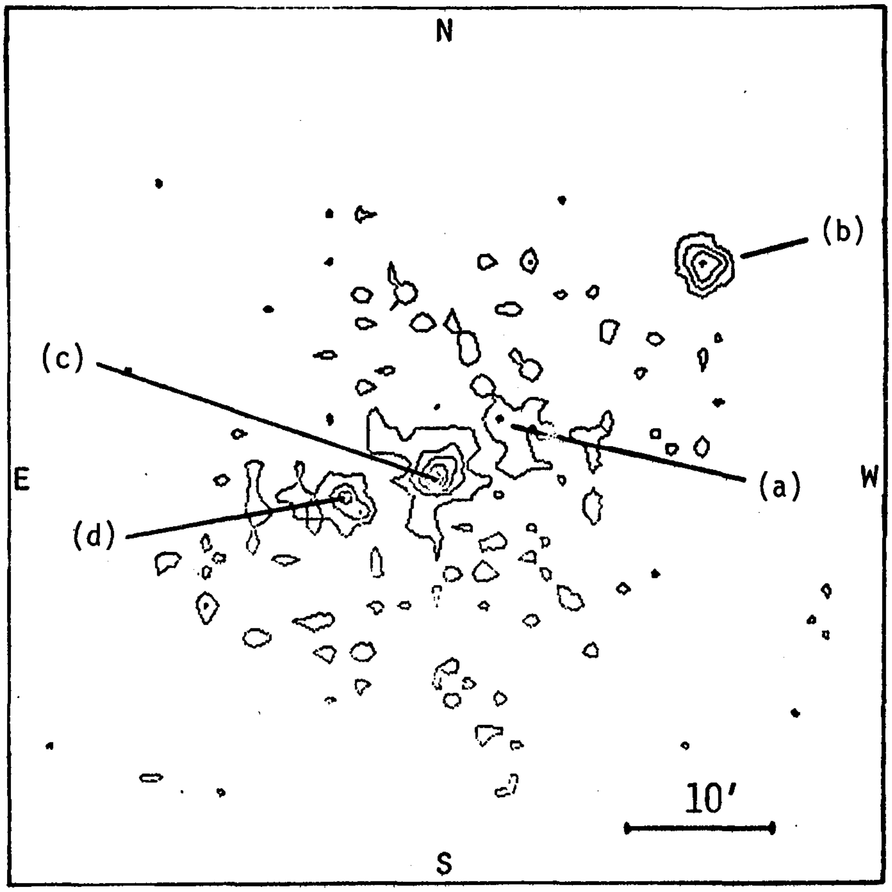


Figure 3. Multifrequency spectra of 3C351. Optical data (filled circles) are from O'Dell (March 1979).



(a) KP1703.5+60.9 (c) 3C351

(b) VII Zw674 (d) Seyfert

Figure 4. A 4820-sec IPC image of the 1° × 1° field centered on 3C351. Contour levels are 9, 15, 22.7, 32.3, and 43.6 counts per 64" × 64" cell.

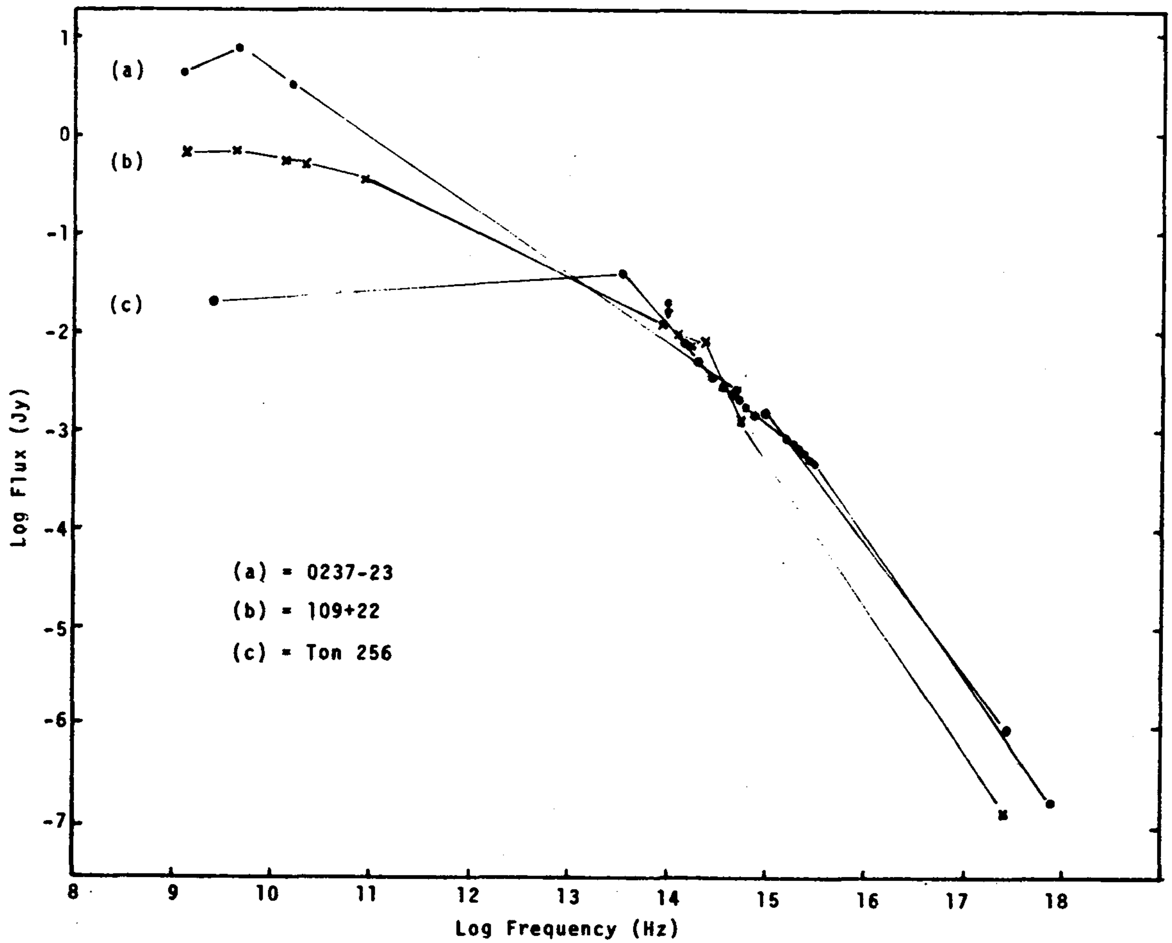


Figure 5. Multifrequency spectra of quasars 0237-23 and Ton 256 and BL Lac object 109+22.

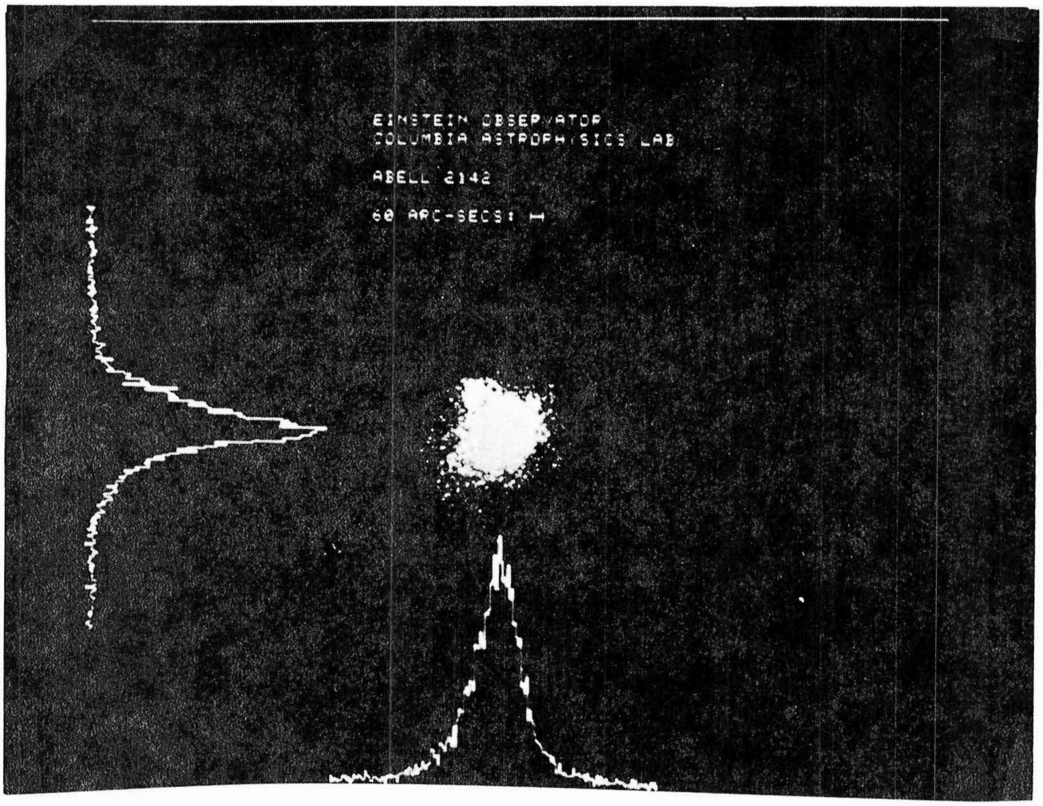
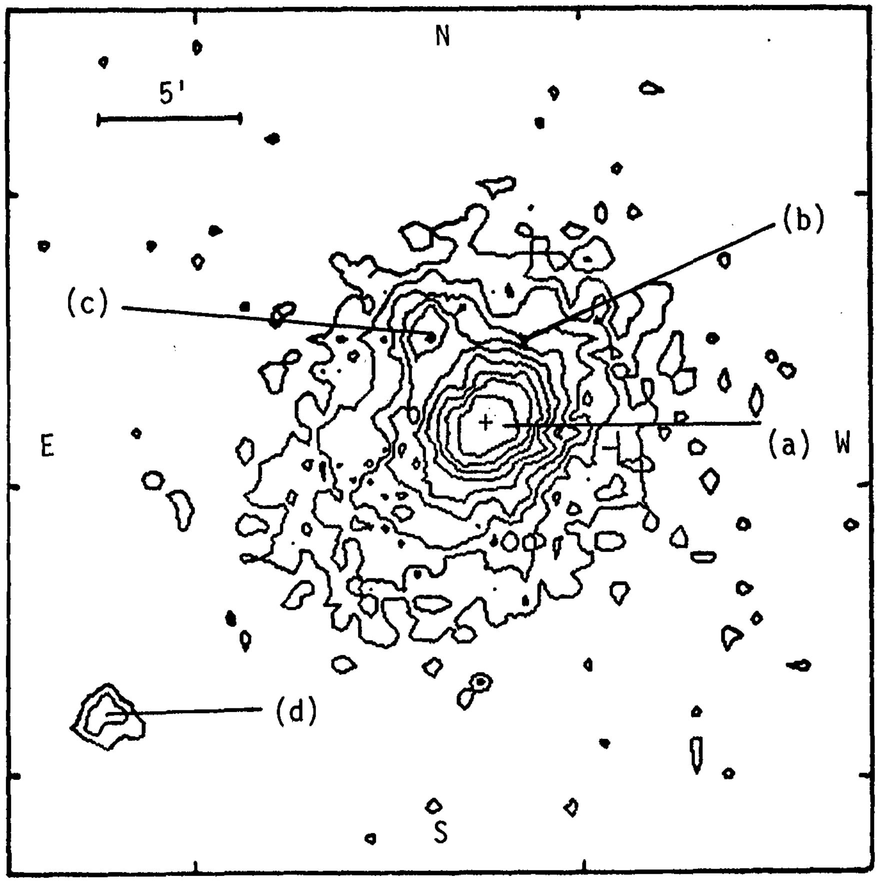


Figure 6a. IPC image of A2142. The line plots show the projected intensity of X-rays from this cluster along NS and EW axes.



(a) Optical center: $15^h56^m13^s$, 27°22'27"

(b) Radio head-tail galaxy

(c) Seyfert 1E1557+2712, z = 0.066

(d) Unidentified point source: $15^h56^m25^s$, 27°25'40"

Figure 6b. A 5900-sec IPC image of A2142 cluster.

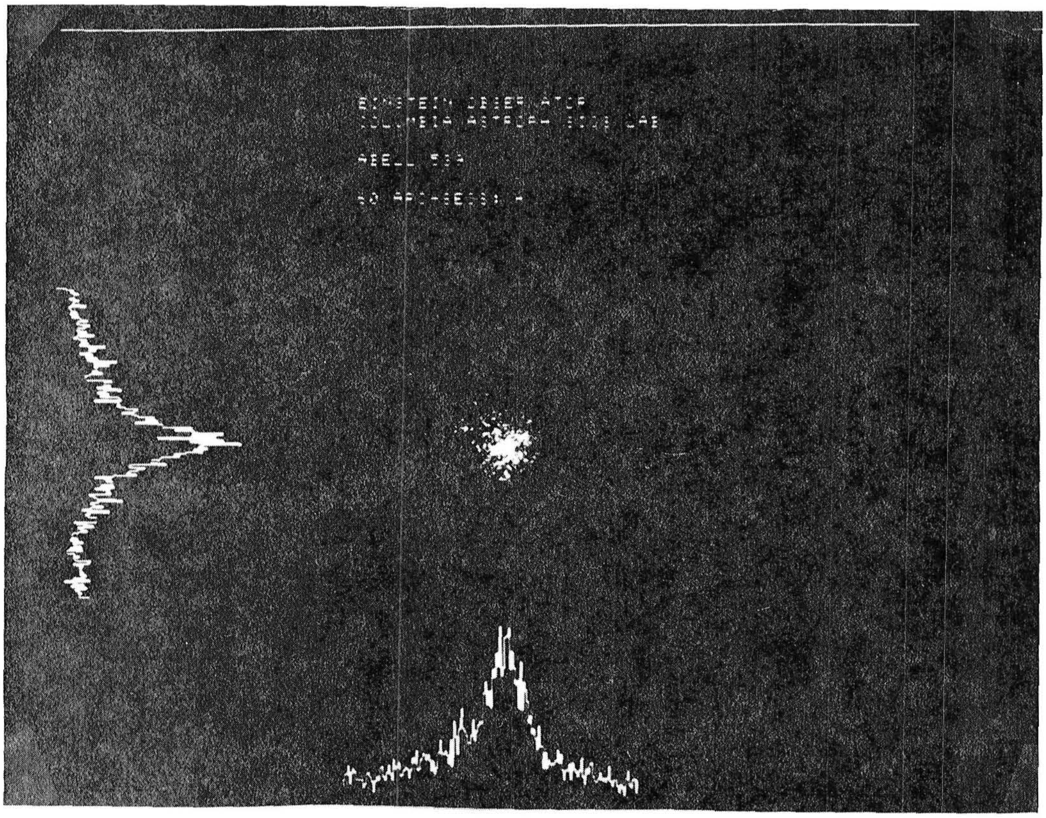
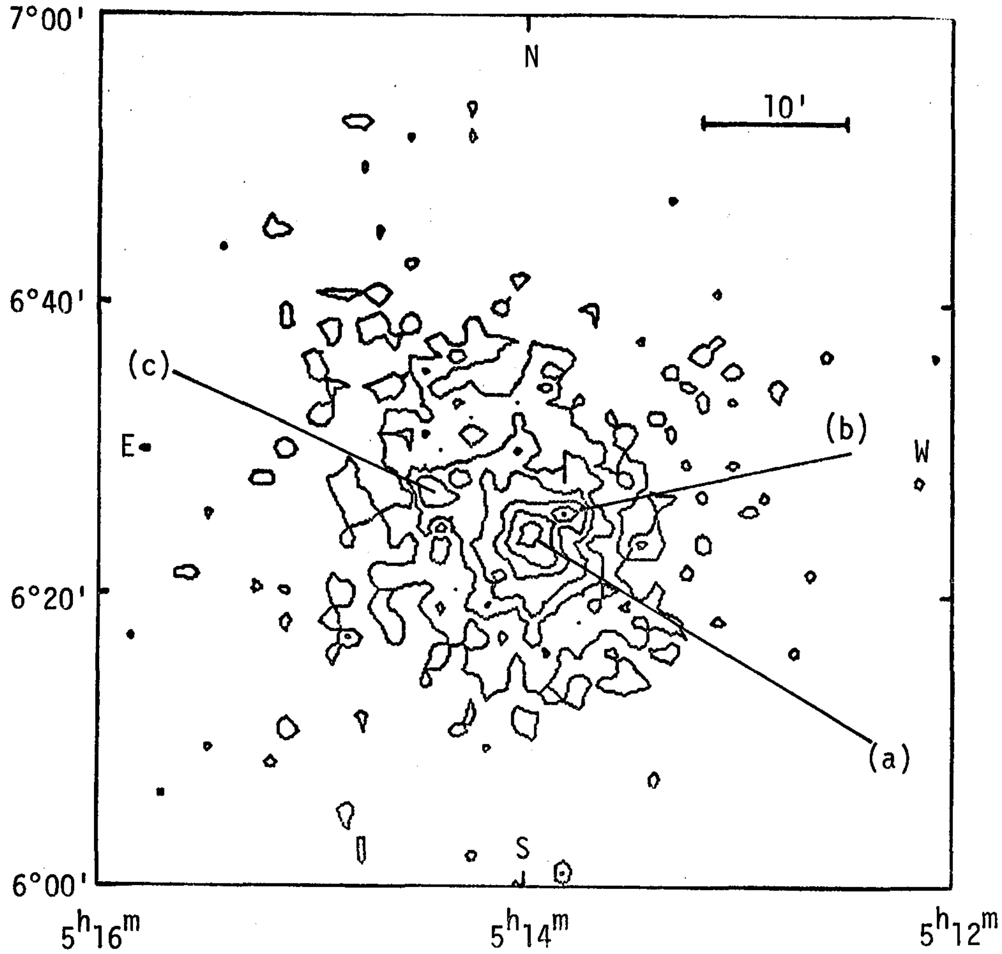


Figure 7a. IPC image of A539. The line plots show the projected intensity of X-rays from this cluster along NE and EW axes.



(a) Pair of galaxies: $5^h13^m54^s$, 6°24'10"

(b) Zwicky galaxy: $5^h13^m46^s$, 6°25'45"

(c) Unidentified: $5^h14^m23^s$, 6°27'10"

Figure 7b. A 5200-sec IPC image of A539 cluster. The six contour levels are 9, 15, 23, 32, 44, and 57 counts per 64" × 64" cell.

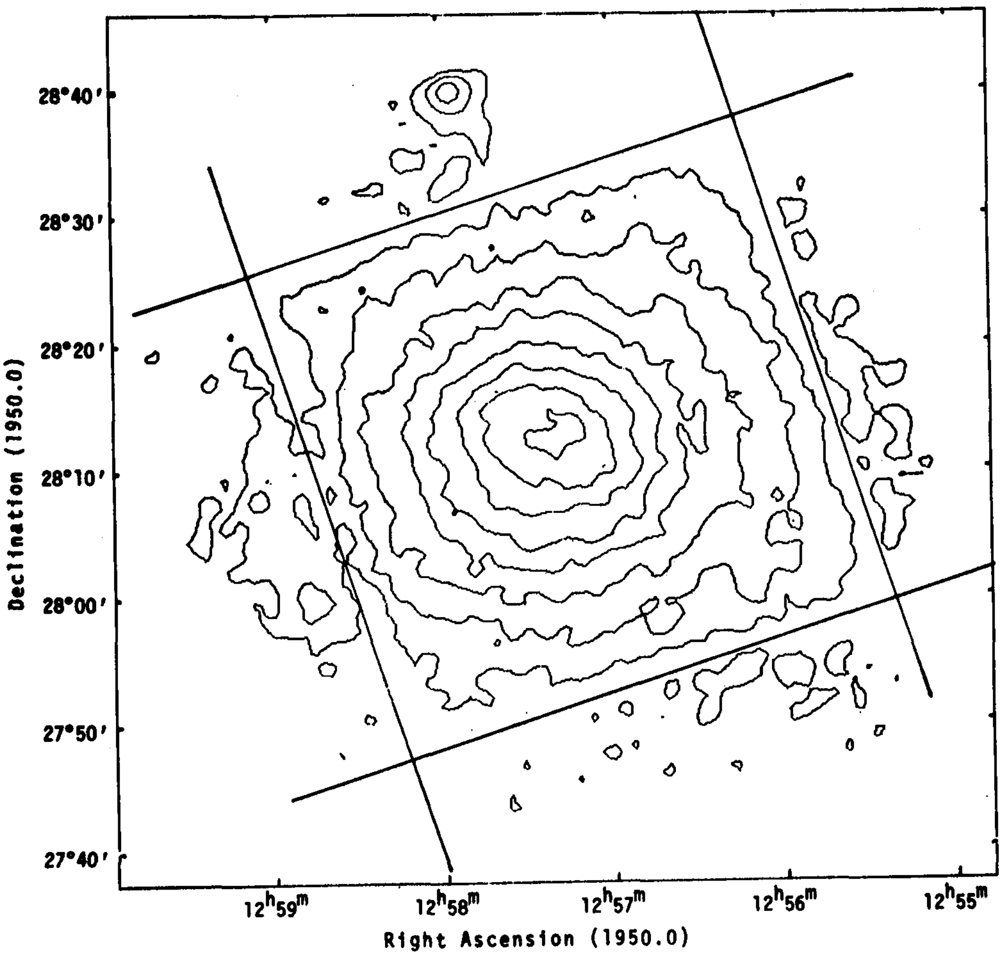


Figure 8. An 8000-sec IPC image of the center of the Coma cluster. The point source near the top of the field is X Comae, A Seyfert galaxy. The intersecting lines indicate the location of the shadows of the support structure.

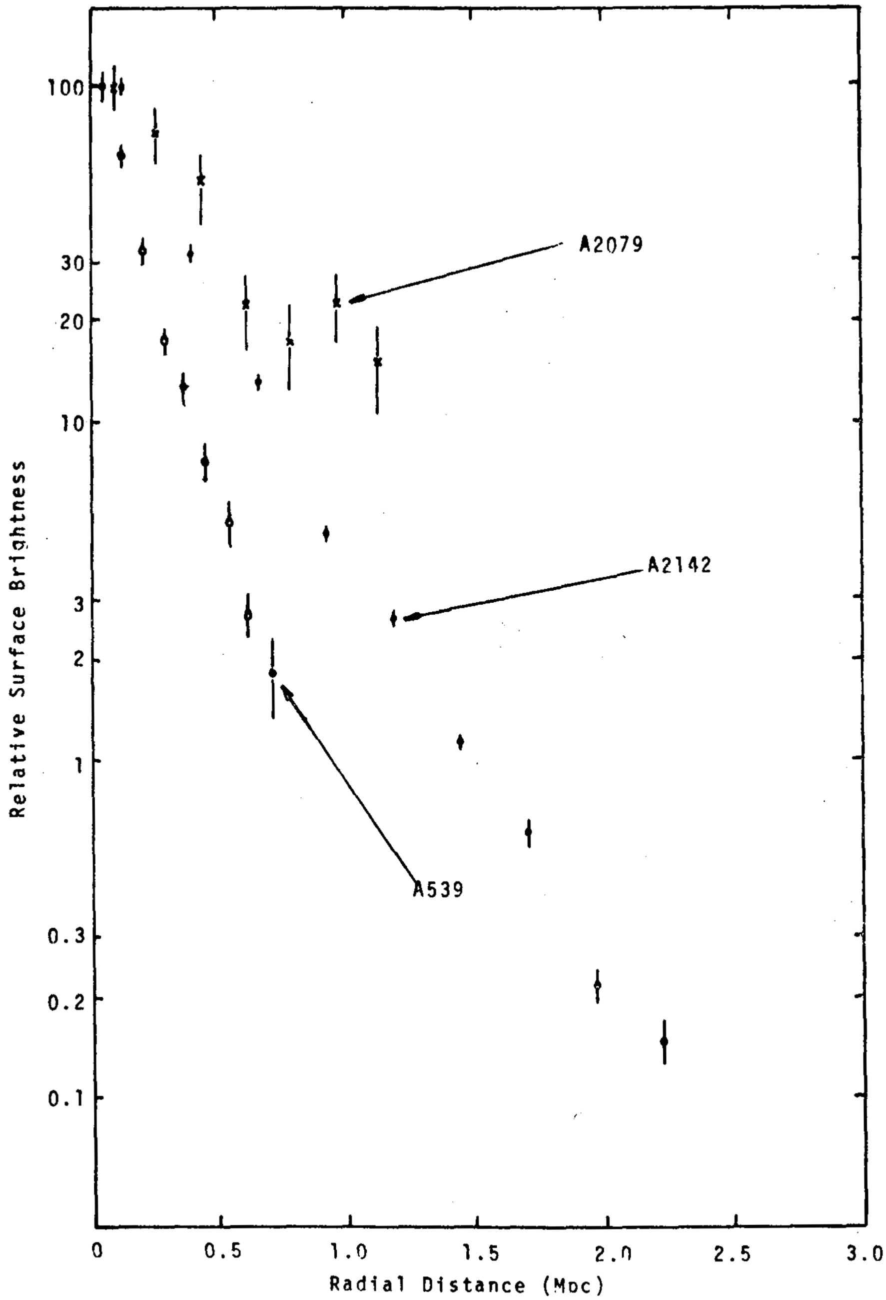


Figure 9. Radial surface brightness distribution of X-rays for A2079, A2142, and A539.