WQ 2059-247: AN UNUSUAL HIGH REDSHIFT X-RAY CLUSTER

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ABSTRACT

We report x-ray, optical, and radio observations of a high redshift, Bautz-Morgan type I cluster of galaxies. The cD galaxy contains a powerful, flat spectrum radio source coincident with the possibly stellar nucleus. The cluster is an extremely luminous x-ray source; however, unlike nearby luminous x-ray clusters the x-ray spectrum appears to be rather soft. We suggest two possible interpretations of the source: either the intracluster gas is much cooler in high redshift clusters because they are less relaxed, or the x-ray and radio emissions from WQ 2059-247 are the result of a non-thermal QSO/BL Lac type object in the nucleus of the cD.

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I. INTRODUCTION

The study of clusters of galaxies at high redshift can provide a wealth of information on the formation and evolution of clusters, the origin of the intracluster medium, the nature and origin of cD galaxies and the evolution of non-thermal nuclear sources (quasars, radio galaxies, etc.). As the largest organized structures in the universe, clusters may provide cosmological 'markers' for determining the structure of the universe. Unfortunately, the number of known high redshift clusters is small, and they have been discovered in an unsystematic manner.

White and Quintana (1980) have made an optical survey of clusters covering a wide range of properties and distances. The clusters extend from Abell's distance group 0 through 7 (Abell 1958), and out to an estimated z of 0.4. The survey was made on the ESO/SRC J copies, which are very deep. Information includes cluster richness, Bautz-Morgan (B-M) type (Bautz and Morgan 1970), compactness, and other properties. The uniform classification of clusters over so wide a range of redshift is essential to provide a proper sample for the study of cluster evolution. We are presently investigating the x-ray, radio, and optical properties of a select group of high redshift clusters from this survey.

We report here on one cluster from this survey, WQ 2059-247, having extraordinary x-ray, optical, and radio properties. Optically this cluster is dominated by a cD galaxy, whose nucleus (which may be stellar) contains a strong, flat-spectrum radio source. The cluster is extremely luminous in x-rays, and appears to have a soft x-ray spectrum. Thus, the present observations may indicate that high redshift clusters have intracluster gas which is considerably cooler than that in nearby clusters (see also Perrenod and Henry 1980). On the other hand, we also suggest an alternative model in which the radio, optical, and x-ray radiation all arise from a QSO/BL Lac type object in the nucleus of the cD galaxy.

II. OPTICAL OBSERVATIONS

A reproduction of the region surrounding WQ 2059-247 taken from the ESO/SRC J copy is shown in Figure 1a (Plate 1). The cD galaxy at the center of this cluster is indicated on the plate. WQ 2059-247 was classified as a cosmological cluster by White and Quintana (1980), with an estimated redshift based on the magnitude of the tenth brightest galaxy ($m_{10}(B) = 21.0 \pm 0.3$) of $z = 0.4$. The distance scale was calibrated by assuming that Abell's $m_{10} = 18.0$ is equivalent to a redshift $z = 0.20$ (Abell 1958) and by using standard K-corrections (Whitford 1975) and assuming standard elliptical colors ($B-R = 1.60$). The magnitudes were estimated by comparison to galaxies with known photoelectric magnitudes in the cluster A1146 on an equivalent ESO/SRC film copy. The redshift estimate is supported by comparisons of WQ 2059-247 with images on Palomar-Schmidt IIIa J plates of Gunn-Oke clusters with known redshifts. The errors involved in redshift estimates of this sort can be quite large, however. For clusters at this redshift, only the brightest galaxies are detectable on ESO/SRC plates. Thus, it is difficult to determine accurately the richness. However, the cluster must be relatively rich; we would estimate that it is Abell richness class 1-2 (between A2199 and Coma in richness). WQ 2059-247 is a B-M type I, compact cluster with an estimated radius (see White and Quintana 1980) of 200 arcsec. If $z = 0.4$, $H_o = 50h_{50}$ km/sec/Mpc, and $q_o = 0$ (the standard values used throughout this paper), this corresponds to $1.4\ h_{50}^{-1}$ Mpc.

The cD galaxy is shown at higher magnification in Figures 1b and

1c (Pl to 1), at two exposure levels. In Figure 1b, a deep exposure, the largest extent of the cD envelope visible on the film copies is indicated with a dashed line. The diameter is approximately 35 arcsec, corresponding to 250 h_{50}^{-1} kpc. This is consistent with the classification of the galaxy as a cD. Figure 1c, a lighter exposure, illustrates the nuclear region of the cD. The nuclear region is apparently unresolved, with an image diameter of 3 1/2 arcsec. The magnitude of the nucleus is $m_B = 19.4 \pm 0.3$. Unfortunately, we do not have access to the ESO/SRC R copies; however, this region overlaps with the southern zone of the Palomar Survey. Although the images of the cD nucleus are near the plate limits, it is definitely not blue. In Figure 1b, we note that there are at least two secondary nuclei or other galaxies within the projected envelope of the cD, a common feature of cD galaxies.

In the radio and x-ray observations of this region (§III and IV), a second source was discovered south of the cluster (hereafter, the 'southern' source). Although the size of the x-ray error ellipse precludes any definitive optical identification, the radio position is coincident with a blue stellar object of magnitude $m_B = 18 \pm 1$ (estimated from the Palomar Survey). A preliminary spectrum of this object indicates that it is a background quasar with a redshift of $z = 0.96$ (John Stocke, private communication).

The optical positions of the cD nucleus and southern source (quasar) are given in Table 1.

III. RADIO OBSERVATIONS

As part of a VLA survey of high redshift clusters (Jaffe 1980), the cluster region was observed on the night of 24-25 July 1979, when the

VLA consisted of 14 25m telescopes with baselines from 25m to 17 km. Because of atmospheric fluctuations at low elevations we only included baselines shorter than 8 km in the reduction. The telescope was tuned to 1460 MHz with a bandwidth of 50 MHz. We observed ten 6 minute 'cuts' spaced evenly in hour angle from -3^h to 3^h. The map showed two unresolved sources (<5 arcsec). The stronger source has a flux $S_{1460} = 58 \pm 4$ mJy and was coincident with the optical nucleus of the cD (see Table 1). The second, southern source had a flux of $S_{1460} = 31 \pm 2$ mJy, and was coincident with the quasar described in §II. In addition, we obtained a single 10 minute scan of the region at 4885 MHz on the VLA about two months later. This revealed an unresolved source (<3 arcsec) with a flux of $S_{4885} = 45 \pm 5$ mJy coincident with the cD nucleus, with some confusing emission on a scale of 1 arcmin. The limited data did not allow the mapping of this emission. The southern source was beyond the field of view in this observation.

The spectral index of the cD nucleus from 1460 to 4885 MHz is -0.2 ± 0.1. At a redshift of $z = 0.4$, the luminosity per unit frequency is $P_{1460} = 5.9 \times 10^{25}$ W H_z^{-1} in the rest frame of the source. Sources of this luminosity or with flat spectra are unusual in brightest cluster galaxies. The local radio luminosity function of Auriemma et al. (1976) predicts that only 1 in 3000 such galaxies will be radio emitters with this or higher luminosity, regardless of spectrum. Moreover, most dominant cluster galaxies have very steep radio spectra. However, it is only fair to point out that the cD in WQ 2059-247 is not unique in its radio properties; NGC 1275 (3C 84) in the Perseus cluster is similar. At $z = 0.4$, NGC 1275 would have fluxes of $S_{1460} \approx 70$ mJy and $S_{4885} \approx 55$ mJy (Gisler and Miley 1979).

IV. X-RAY OBSERVATIONS

The cluster was observed for 3135 seconds with the Imaging Proportional Counter (IPC) on the Einstein X-Ray Observatory (Giacconi et al. 1979). Two sources were detected near the center of the field, a strong source at the cluster center and a weaker source about 4 arcmin south of the cluster center. By binning the data horizontally, vertically, and radially from the center of the cluster source and comparing to similar profiles for isolated point sources, we found that the two sources were apparently distinct; no significant evidence for any extended emission linking the two was found. The position of the cluster source and southern source are given in Table 1. On Figure 1a (Plate 1) we show the 68% confidence intervals for the positions of the centers of the two x-ray sources superimposed on the optical image of the cluster. The position of the cluster source is clearly consistent with the position of the nucleus of the cD galaxy. The southern source is well-separated from the cluster center. In the analysis and discussion which follow, we will assume that the southern source is in fact the background quasar described in §II and III. Comparison with other fields we have observed for comparable periods indicate such serendipitous sources are reasonably common.

To determine the flux from the cluster, we determined a flux for the southern source, and the flux from the entire region, and then subtracted the two. The background was determined from the SDF file; however, results for backgrounds determined from blank regions in the same field are similar within the errors. We found 38.8 ± 6.9 net counts (.5 – 3 keV) from the southern source, and 393.1 ± 23.0 total net counts for the region, which yields 354.3 ± 24.0 net counts for the cluster source. If we assume that both sources have power law photon spectra with an index of 2, we find observed fluxes of $1.57 \pm .11 \times 10^{-3}$ ph/cm^2 sec for the cluster source and $1.57 \pm .28 \times 10^{-4}$ ph/cm^2 sec for the southern source in the energy range of .5 – 3 keV. The hydrogen column density towards the source can be interpolated from the tables of Tolbert (1971) as $N_H = 6.5 \pm 1.0 \times 10^{20}$ cm^{-2}. The luminosity of the cluster source corrected for absorption in our galaxy and assuming $z = 0.4$, is $L = 3.83 \pm .26 \times 10^{45}\ h_{50}^{-2}$ ergs/sec for the energy range .5 – 4.5 keV in the rest frame of the cluster. We again assumed an E^{-2} photon spectrum, although the result for a thermal spectral with kT = 2 keV is identical within the errors.

The observed pulse height count distribution from the cluster source is shown in Figure 2. Apparently, the source has a soft spectrum. Because of gain variation problems within the IPC, spectral fits from pulse height discributions are not reliable. However, from a comparison with IPC observations of other sources with known spectra, we estimate that if WQ 2059-247 emits by thermal bremsstrahlung and line emission with solar abundances (Sarazin and Bahcall 1977), the predominant emission temperature must be kT $\lesssim$ 4 keV in the rest frame of the cluster. However, this estimate is very tentative; a more accurate determination of the temperature from these data must await the calibration of the variable gain on the IPC.

We have determined the radial distribution of x-ray counts around both sources, and compared to the point spread function of the instrument as determined by observing known point sources. Both sources are apparently unresolved; however, their proximity makes this result somewhat ambiguous. Conservatively, we have estimated that at least 80%

of the flux from the source comes from within a circle of radius 45" for the cluster source and 90" for the southern source.

V. DISCUSSION

WQ 2059-247 is one of the most luminous x-ray clusters ever observed. It is three times as luminous as 3C295, the strongest cosmological cluster detected by Henry et al. (1979). It is as bright as or brighter than the most luminous nearby clusters, such as A401, A1146, and A2029 (Jones and Forman 1978; McHardy 1978). These are all B-M type I clusters, as is WQ 2059-247. The x-ray source associated with WQ 2059-247 is also rather compact. If it is fit by an isothermal sphere, its x-ray core radius is $\lesssim .23\ h_{50}^{-1}$ Mpc.

At first sight, the x-ray properties of WQ 2059-247 would seem to form a natural extension of the properties of nearby clusters. In §II and §III, we showed that WQ 2059-247 is a rich, compact cD cluster (B-M type I) with a strong radio source. Observations of nearby clusters indicate that the most luminous x-ray clusters are B-M type I's (Bahcall 1974), and that in these clusters the x-ray surface brightness is sharply peaked around the central cD galaxy, with a core radius of about .25 Mpc (Jones et al. 1979). Moreover, strong x-ray emission is often found to correlate with the presence of a strong radio source (McHardy 1978).

However, while the strength of the radio and x-ray emission can be interpreted as an extension of properties of nearby clusters, the x-ray and radio spectra cannot. WQ 2059-247 is softer than the very luminous x-ray sources associated with most nearby x-ray clusters. The B-M type I cluster A2199 has a low temperature kT ≈ 3 keV (Mushotzky et al. 1978), but is more than an order of magnitude less luminous than WQ 2059-247.

While there is evidence that many clusters have cooling components in their cores (Canizares et al. 1979; White and Silk 1980), the total luminosities associated with these cooling cores are much smaller than the luminosity of WQ 2059-247.

The flat radio spectrum of the radio source associated with the cD galaxy in WQ 2059-247 is also unusual for either a radio source in a cD or a strong x-ray cluster radio source. It is more typical for the very compact radio sources associated with quasars and BL Lac objects.

Given these problems with interpreting the emission from WQ 2059-247 with thermal emission from intracluster gas, we suggest the possibility that the x-ray emission we have detected and also the nuclear optical emission from the cD might all originate from the same nonthermal point source which produces the compact radio source. In Figure 3, we show the radio, optical, and x-ray fluxes observed for this source; the x-ray and optical fluxes were corrected for absorption in our galaxy corresponding to a column density of hydrogen $N_H = 6.5 \times 10^{20}$ cm^{-2} (see §IV). The radio (4885 MHz) to optical spectral index is $\alpha_{ro} = -0.50$, while the optical to x-ray index is $\alpha_{ox} = -0.87$. These values are similar to those typically found for quasars and BL Lac objects, although the x-ray to optical luminosity ratio is somewhat higher than normal (Tananbaum et al. 1979). If the radio, optical, and x-ray emission of this object do arise for a non-thermal point source, the total luminosity of this nonthermal point source would be larger than 10^{46} h_{50}^{-2} ergs/sec, which would put it in the class of quasars or BL Lac objects.

Two weak arguments slightly favor a BL Lac object. First, the optical nucleus is not blue, as it would be if it had strong emission lines. Second, the ratio of x-ray to optical luminosity is larger than unity. This may indicate that the source is extremely compact and is therefore more likely to be associated with a BL Lac object or optically violently variable quasar.

Thus, if the x-ray emission from WQ 2059-247 is diffuse, thermal emission from intracluster gas, the gas is considerably cooler than that found in nearby luminous x-ray clusters. We note that the evolutionary models of Perrenod (1978) predict that clusters at $z = 0.5$ have average x-ray temperatures as much as a factor of two lower than those in average nearby clusters. Alternatively, the x-ray emission from WQ 2059-247 may originate in the nonthermal point source at the center of the cD galaxy. If so, it will be the first time a quasar or BL Lac object has been discovered in a previously identified galaxy.

Additional observations of WQ 2059-247 can resolve this ambiguity in its interpretation. An optical spectrum of the cD would provide an accurate redshift for the system, and might show the emission lines or nonthermal continuum expected if the system were a QSO/BL Lac object. A direct optical plate from a large telescope should determine whether the nucleus is pointlike or extended; similarly, a high resolution x-ray map would show whether the emission arises from a diffuse gas or a point source at the cD nucleus. Finally, all of these observations can be used to test whether emission from the object varies significantly, as might be expected for a BL Lac object.

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TABLE 1 OPTICAL, RADIO, AND X-RAY POSITIONS

Source		R.A. (1950)	Dec
cD nucleus/cluster	Optical	$20^h59^m14.57 \pm .12^s$	$-24°43'53.2 \pm 2.0''$
	Radio	$20^h59^m14.56 \pm .18^s$	$-24°43'56.5 \pm 3.0''$
	X-ray	$20^h59^m15.1 \pm 2.3^s$	$-24°43'31 \pm 57''$
Southern/quasar	Optical	$20^h59^m17.25 \pm .12^s$	$-24°47'46.0 \pm 2.0''$
	Radio	$20^h59^m17.28 \pm .18^s$	$-24°47'45.7 \pm 3.0''$
	X-ray	$20^h59^m18.9 \pm 4.3^s$	$-24°47'17 \pm 53''$

FIGURE CAPTIONS

Figure 1a: Finding chart for the region of WQ 2059-247 from ESO/SRC J copy. The plate scale is 6.71 arcsec/mm. The cD and southern object/quasar are labelled. The x-ray position error ellipses for the two sources are shown as dashed lines.

1b: A larger scale, deep exposure of the cD. The maximum extent of the envelope visible on ESO/SRC J film copy is shown as a dashed contour. The plate scale is 1.34 arcsec/mm.

1c: A larger scale, shorter exposure of the cD at the same scale as 1b, to show the unresolved nucleus of the cD.

Figure 2: A histogram of the IPC pulse height distribution from WQ 2059-247. Each bar gives the number of net source counts in the photon energy range shown; the lines in the center of the bars give the 1σ uncertainties.

Figure 3: The radio, optical, and x-ray fluxes from WQ 2059-247.

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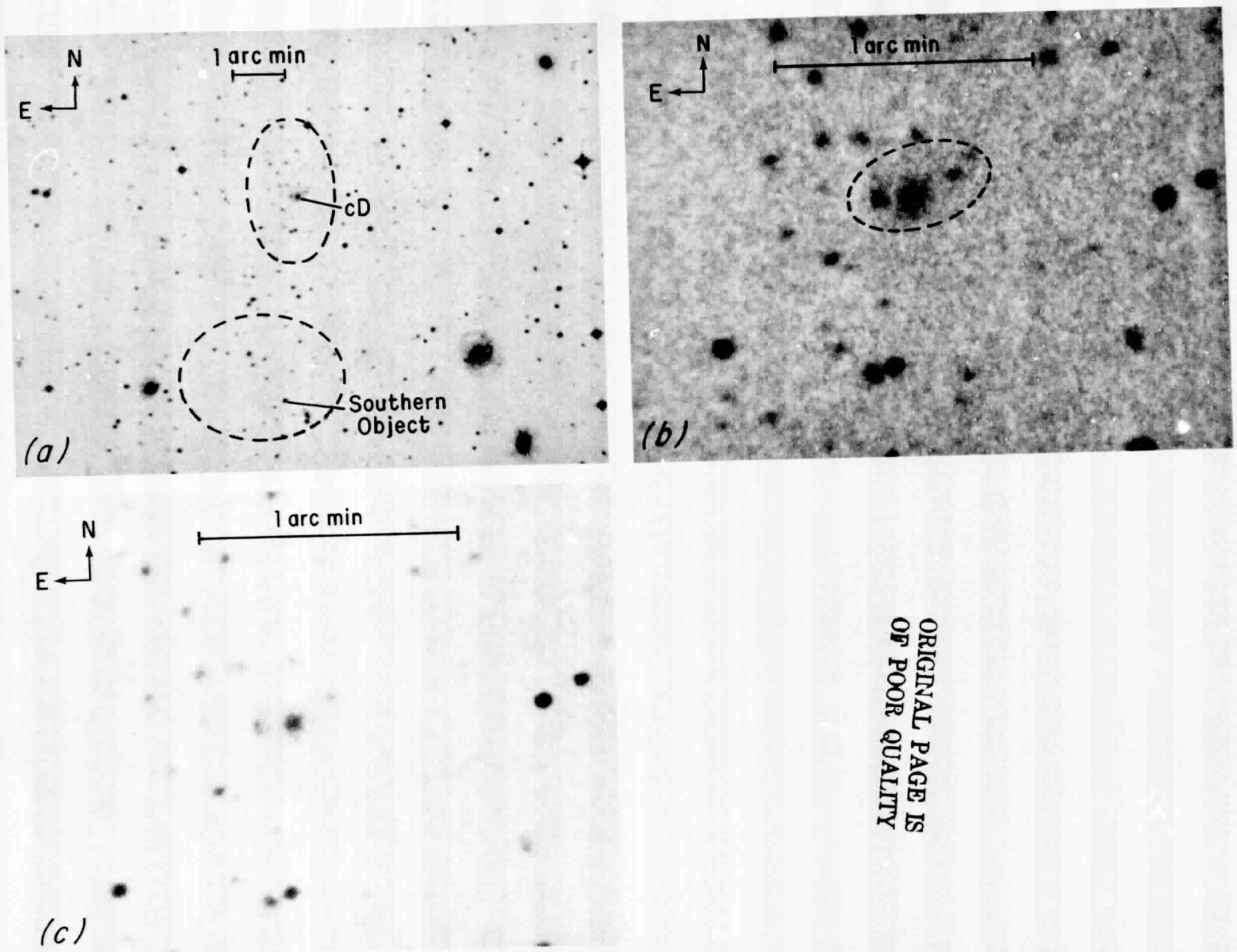
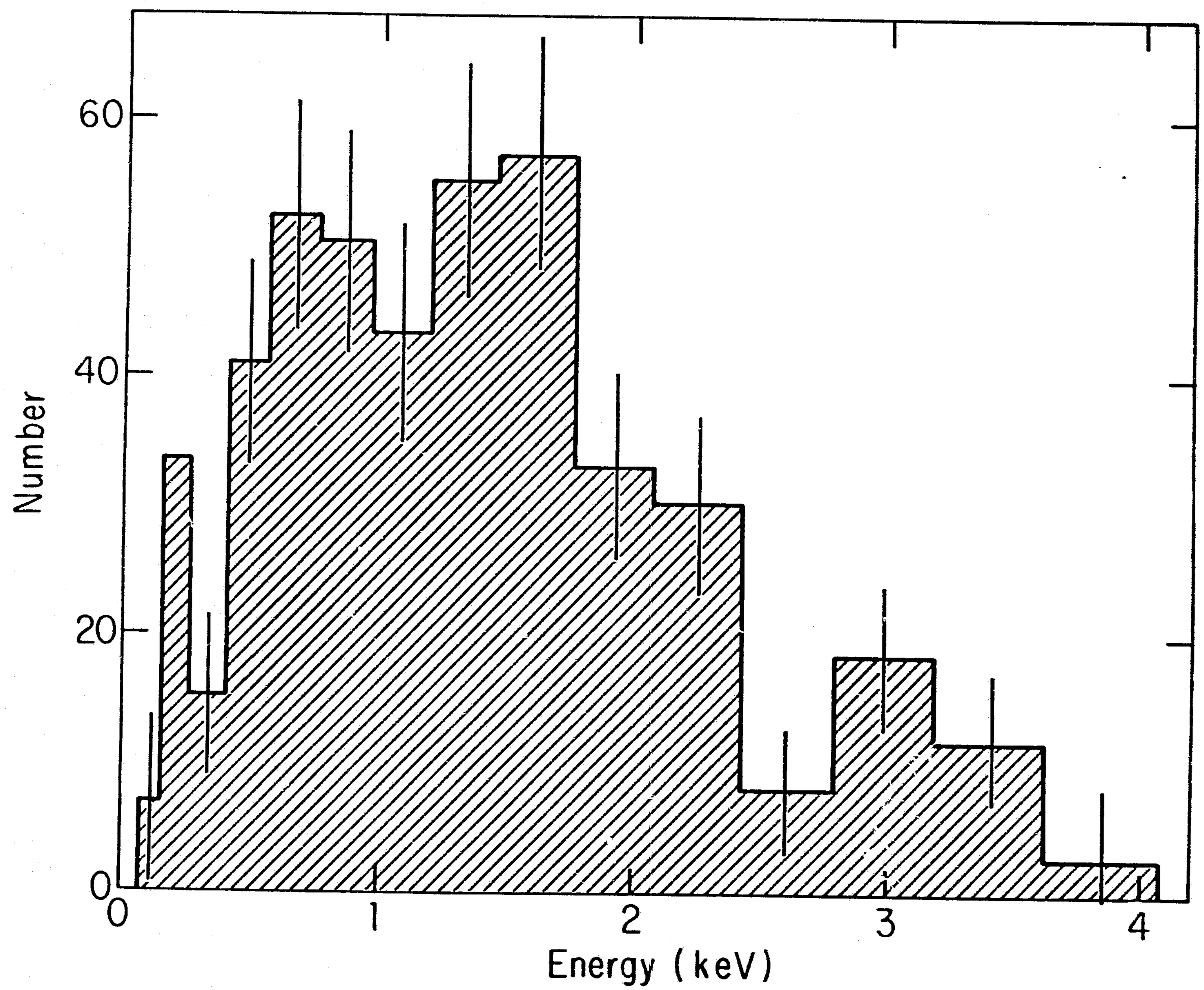
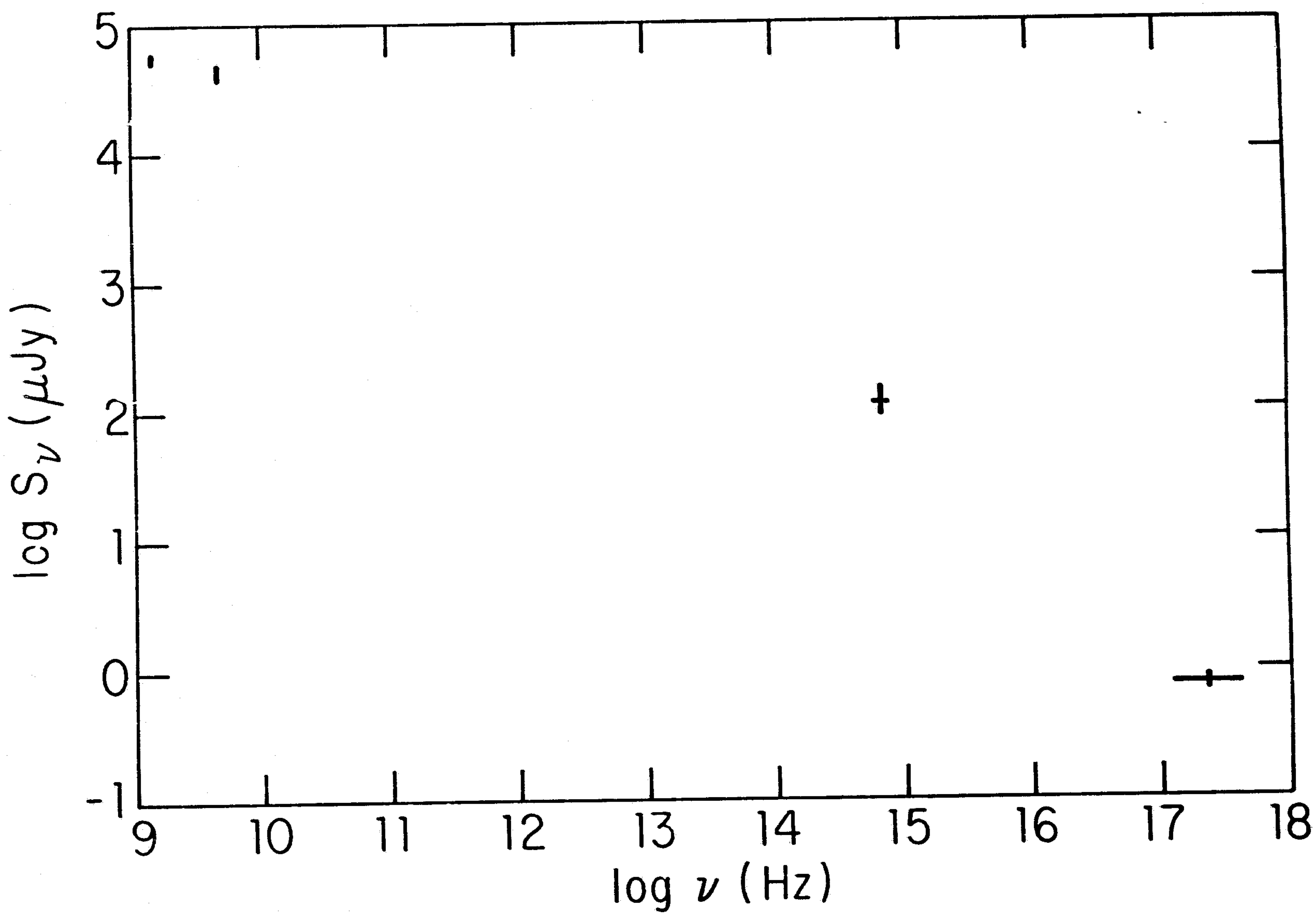
CANADA



1 arc min
N
E
cD
Southern
Object
(a)
1 arc min
N
E
(b)
1 arc min
N
E
(c)



60
40
20
0
Number
0
1
2
3
4
Energy (keV)



log S_ν (μJy)
log ν (Hz)