THE ASTROPHYSICAL JOURNAL, 275:1–7, 1983 December 1

EINSTEIN X-RAY OBSERVATIONS OF OPTICAL-RADIO SELECTED AREAS

P. KATGERT[1]
Sterrewacht, Leiden, The Netherlands
TRINH X. THUAN[1]
Astronomy Department, University of Virginia
AND
ROGIER A. WINDHORST[1]
Sterrewacht, Leiden, The Netherlands
Received 1983 February 14; accepted 1983 May 6

ABSTRACT

We present X-ray observations with the Imaging Proportional Counter aboard the *Einstein Observatory* of fields in SA 57, SA 68, and UMi which possess deep optical and radio coverage. The X-ray sensitivity reached in our survey is $\sim 2 \times 10^{-13}$ ergs cm^{-2} s^{-1} which is comparable to that of the *Einstein* medium sensitivity survey of serendipitous X-ray sources by Maccacaro *et al.* The number of X-ray sources detected is consistent with a log $N(>S)$–log S slope of ~ -1.5. The fraction of extragalactic X-ray sources detected in radio is $\sim 60\%$. The fraction of active galactic nuclei in the X-ray sample is $\lesssim 50\%^{+40\%}_{-25\%}$ with the remaining fraction being composed of clusters and normal galaxies. These results are consistent with those obtained in the *Einstein* medium sensitivity survey.

Subject headings: galaxies: clustering — galaxies: nuclei — X-rays: sources

I. INTRODUCTION

Over the past few years, deep radio surveys at 1412 MHz have been carried out with the 3 km Westerbork Synthesis Radio telescope of several Selected Areas (SA) in the sky, yielding radio sources with flux densities larger than 0.6 mJy (5 σ limit) and with positional uncertainties of at most a few arcseconds (Windhorst, van Heerde, and Katgert 1983). We shall discuss in particular in this paper SA 57, SA 68, and the Ursa Minor fields. Deep optical data also exist for these fields. Kron (1980) has obtained deep ($B_{\rm lim} \sim 23$ mag) Kitt Peak 4 m prime focus plates in the four passbands U ($\bar{\lambda} \sim 3600$ Å), J ($\bar{\lambda} \sim 4650$ Å), F ($\bar{\lambda} \sim 6100$ Å), and N ($\bar{\lambda} \sim 8000$ Å) for SA 57 and SA 68, and deep ($B_{\rm lim} \sim 21$ mag) Palomar 48 inch (1.2 m) Schmidt plates in J and F have been obtained for the Ursa Minor fields.

We have obtained X-ray observations with the Imaging Proportional Counter (IPC) aboard the *Einstein Observatory* of a total of five fields. Two of these are in SA 68, one in SA 57, and two in Ursa Minor. Our primary aim here is to investigate the relationship among the radio, optical, and X-ray emission in extragalactic objects. We describe the observations in § II. We discuss the identifications in § III and compare our findings with those of previous medium sensitivity surveys (Maccacaro *et al.* 1982, hereafter M) in § IV.

[1] Guest Investigator, *Einstein Observatory*.

II. OBSERVATIONS

Details about the X-ray observations are given in Table 1. A 5 σ limit ($S_{\rm lim}$) was adopted to be the limit above which sources were accepted for inclusion in a complete sample. This 5 σ limit is the same as the one adopted by M in their surveys so that our data can be directly compared to theirs. Moreover, as discussed by M, a 5 σ limit is needed to minimize the number of spurious sources and to satisfy the requirement of the maximum likelihood method used to determine the log N − log S parameters. The σ's, the fluxes, and positions of the sources within the central 32 × 32 arcmin^2 of the IPC images (i.e., inside the "ribs") were determined in the manner described by M. Table 1 shows that $S_{\rm lim}$ varies between 1×10^{-13} and 3×10^{-13} ergs cm^{-2} s^{-1}. This means that the sensitivity of the present survey overlaps with the faint end limit of the medium sensitivity survey of serendipitous X-ray sources by M, whose flux levels vary between 7×10^{-14} and 5×10^{-12} ergs cm^{-2} s^{-1}. The flux limit of Giacconi *et al.* (1979) survey is 2.6×10^{-14} ergs cm^{-2} s^{-1} (1–3 keV), about a factor of 8 smaller than the flux limit of the present survey. In addition to the observations listed in Table 1, R. Kron and P. Boynton kindly gave us the permission to examine their IPC frame of SA 68, I7597 which partially overlaps our frames, I10431, and I10432. Their frame is centered on $\alpha(1950) = 00^{\rm h}14^{\rm m}00^{\rm s}$ and $\delta = 15°45'00''$ and has $S_{\rm lim} = 9.8 \times 10^{-14}$ ergs cm^{-2} s^{-1}. No new source was found.

For sources outside the "ribs," the standard source

TABLE 1

Einstein IPC Observations of Selected Areas

Area	$\alpha(1950)$[a]	$\delta(1950)$[a]	Observation	Net Exposure Time (s)	S_{lim} (ergs cm^{-2} s^{-1})
SA 68	00h14m20s	16°20′00″	I10431	18,900	10.7×10^{-14}
	00 15 20	15 35 00	I10432	17,000	11.4×10^{-14}
SA 57	13 06 15	29 39 03	I3045	7600	22.1×10^{-14}
Ursa Minor	14 04 12	72 21 00	I10197	5900	30.7×10^{-14}
	14 15 48	72 21 00	I10198	5700	29.7×10^{-14}

[a] The coordinates given are those of the frame center. An IPC frame has an area of 32 × 32 arcmin^2 inside the "ribs."

fitting procedure was used. The same nominal 5 σ limit for source detection was adopted for the outer parts. No independent estimate can be made of the completeness limit in these outer parts. We expect the sample of sources found outside the ribs to be far from complete, because the actual flux completeness limit probably increases towards the edges of the images.

The positions and fluxes of the detected X-ray sources in the complete ("inner") sample are given in Table 2. Those of sources in the outer parts are given in Table 3. The real uncertainties in the X-ray positions are not very well known. The quoted 90% confidence radius of $\sim 1'$ would correspond to a σ of $\sim 0.6'$ for normally distributed errors. The fluxes of the sources in Table 2 correspond to the energy band 0.3–3.5 keV; those given in Table 3, to the energy band 0.15–4.5 keV.

III. IDENTIFICATIONS

We have attempted to identify all sources in Tables 2 and 3 in both optical and radio bands. Because of the relatively large positional uncertainty of the X-ray positions, optical identifications cannot be made on the

TABLE 2

Selected Areas X-Ray Sources in Complete Sample

Source	$\alpha(1950)$	$\delta(1950)$	$10^{14}S$(0.3–3.5 keV) (ergs cm^{-2} s^{-1})	(S_x/S_v)[a]	Δ(Radio–X-Ray) (arcsec) Δα	Δδ	Δ(Optical–X-Ray) (arcsec) Δα	Δδ	Optical Identification
SA 68 A	00h13m24s	15°57′25″	25.9 ± 2.6[b]	0.15	−45″	51″	−42″	53″	Galaxy (in group?)
SA 68 B	00 14 38	16 27 20	16.2 ± 2.4	...	...	...	...	...	...
SA 68 C	00 14 47	16 13 55	35.0 ± 3.1	2.7×10^{-4}	...	...	6	2	Bright star(s)
SA 68 D	00 15 48	15 23 35	13.4 ± 2.6	1.4	9	9	9	5	QSO
SA 57 A	13 05 28	29 42 10	43.8 ± 5.4	3.7	−27	−23	−28	−23	cD gal in cluster

[a] The formula log $(S_x/S_v) = \log S_x + m_v/2.5 + 5.37$ as given by M, has been used. When there is no optical identification on the 4 m blue and red plates, a limit of 22 mag in V has been adopted. Ellipses occur when there are no radio and optical identifications.
[b] The X-ray emission is extended at a position angle of $\sim 130°$.

TABLE 3

Selected Areas X-Ray Sources not in Complete Sample

Source	$\alpha(1950)$	$\delta(1950)$	$10^{14}S$(0.15–4.5 keV) (ergs cm^{-2} s^{-1})	(S_x/S_v)[a]	Δ(Radio–X-Ray) (arcsec) Δα	Δδ	Δ(Optical–X-Ray) (arcsec) Δα	Δδ	Optical Identification
SA 68 E	00h13m17s	16°03′15″	16.4 ± 2.5	≳24	−37″	−60″	...	...	...
SA 68 F	00 15 12	16 03 00	27.0 ± 3.0	6.3×10^{-5}	...	...	30″	13″	Bright star
SA 68 G	00 15 59	16 09 30	67.4 ± 7.7[b]	12	...	...	−3	5	Cluster
SA 68 H	00 17 19	15 40 40	35.9 ± 5.0	...	...	...	...	...	...
UMi A	14 07 27	72 35 30	45.6 ± 7.7	≳67	15	−41	...	...	...

[a] See Note a in Table 2.
[b] The X-ray emission is extended (White, Silk, and Henry 1981).

basis of positional coincidence alone, especially not on the very deep ($B_{lim} \sim 23$ mag) optical plate material available for the Selected Areas. There are $\sim$0.6–1.6 $\times 10^4$ optical objects per square degree down to the optical plate limit. Supplementary information, such as slit spectroscopy, is needed to pinpoint the optical identification. For example, slit spectroscopy of many candidates has been essential in the optical identifications of X-ray sources in other *Einstein* surveys (cf. Griffiths *et al.* 1981; Maccacaro *et al.* 1982). The objects identified with the X-ray sources usually show some sign of optical activity such as emission lines in their spectra.

Since we do not possess slit spectroscopic data for our X-ray sources but do have radio data, we have used the radio data as intermediary between the X-ray and optical data to make our identifications. Since the surface density of radio sources to $\sim$1 mJy (Windhorst, van Heerde, and Katgert 1983) is much lower ($\sim$70 per square degree) than that of optical objects down the 4 m plate limit, the number of expected chance coincidences between radio and X-ray is much lower than that for optical and X-ray. The fraction of spurious radio identifications of X-ray sources is estimated to be only $\sim$9% for a 2 σ error area (1′.2 radius). Subsequent optical identification of the proposed radio counterparts can be made on the basis of radio-optical positional coincidence alone. The optical positions have been measured on the 4 m plates with the Berkeley PDS microdensitometer and have an accuracy of $\sim$0″.5. This identification procedure is very reliable when there is good positional agreement between the radio and optical positions (say to within 3″ or 4″).

This scheme has an obvious drawback: no optical identification can be attempted for X-ray sources without radio counterpart. Fortunately, in the present survey, this is the case for only three out of eight extragalactic sources in both the "inner" and "outer" samples.

The optical identifications of the X-ray sources are given in Tables 2 and 3 along with the differences (in arcseconds) between the X-ray positions and the radio and optical positions. Selected X-ray contours superposed on reproductions of the Palomar Sky Survey Red Prints are shown in Figure 1 for SA 68 and in Figure 2 for SA 57. The positions of the radio sources are marked by tick marks or crosses. The following comments can be made about the individual proposed identifications:

SA 68 A.—This source is extended in X-rays and is the bottom source in Figure 1. The radio source ($S_{21} = 6.0 \pm 1.2$ mJy) has a double structure whose lobes are separated by 25″, at a position angle of $\sim$130°. The radio lobes are marked in Figure 1 by the two half-arrows. The optical identification is an elliptical galaxy with $m_{pg} \sim 16$ and $z = 0.083$ (R. G. Kron 1982, private communication), which is probably a member of a loose group. The galaxy seen at the right of the elliptical galaxy is UGC 144 (α[1950] = 00^{h}12^m.8; δ[1950] = 15°57′; 1′.0 × 0′.3, $m_{pg} = 15.7$, Sbc) which is probably also member of that group. This is probably a good identification, despite the large positional difference of $\sim$1′.1. With a Hubble constant equal to 100 km s^{-1} Mpc^{-1} and $q_0 = 0$, the 0.3–3.5 keV luminosity is $\sim 2 \times 10^{42}$ ergs s^{-1}.

SA 68 B.—There exists no radio counterpart; hence, no optical identification is proposed.

SA 68 C.—This source is most probably associated with a $m_v \sim 8.8$ star. The optical and X-ray positions agree to within $\sim$6″. Another possible identification is another star at $\sim$30″ with $m_v \sim 8.8$.

SA 68 D.—This source is most probably associated with a radio QSO ($S_{21} = 2.7 \pm 0.5$ mJy). The optical spectrum of this $m_J \sim 19$ object shows a single broad emission line at 4750 Å (H. Spinrad 1982, private communication). This puts the object at a redshift of either 0.69 (if the line is Mg II) or 2.06 (if the line is C IV), with luminosities of $\sim 10^{45}$ or 4×10^{46} ergs s^{-1} ($H_0 = 100$ km s^{-1} Mpc^{-1}, $q_0 = 0$). The $(J-F)$ color is $\sim$0.5.

SA 57 A.—The most likely identification of this source is a cD galaxy with a redshift of 0.241 (H. Spinrad 1981, private communication) and with $m_F \sim 18$ and $J-F \sim 1.7$. The galaxy is the first brightest cluster member of the Zwicky cluster Zw 1305.4+2941. The 0.3–3.5 keV luminosity is $\sim 3 \times 10^{43}$ ergs s^{-1} ($H_0 = 100$ km s^{-1} Mpc^{-1}, $q_0 = 0$). The source is shown in Figure 2. The cD galaxy is also a slightly resolved radio source ($S_{21} = 2.4 \pm 0.2$ mJy; 4″ ± 1″ × 2″ ± 2″) whose position is given by the two tick marks. There is some evidence that the X-ray emission is extended towards the NE by $\sim$5′ at a position angle of $\sim$45°. The direction of the X-ray elongation is the same as that of the cluster which shows a linear structure (Fig. 2).

SA 68 E.—This X-ray source is probably associated with a $S_{21} = 63.6 \pm 3.4$ mJy radio source. The radio spectral index between 21 cm and 50 cm is ~ -1.10 ($S_{50} = 161 \pm 8$ mJy). There is no optical identification for the radio source down to the 4 m plate limit. The steep radio spectral index suggests that this X-ray source may be associated with a very distant galaxy whose magnitude is fainter than the 4 m plate limit ($F \gtrsim 22.5$). This source can be seen at the top of Figure 1.

SA 68 F.—This source is probably associated with a star with $m_v \sim 7.5$ (at $\sim$33″).

SA 68 G.—*Einstein* HRI observations of this source have been discussed by White, Silk, and Henry (1981). The source is associated with a cluster of galaxies at $z = 0.541$. There is no detectable ($S < 0.6$ mJy) radio source associated with the cluster.

SA 68 H.—There is no radio counterpart; hence, no optical identification is proposed.

UMi A.—This source is most likely associated with a radio source with $S_{21} = 2.1 \pm 0.3$ mJy. There is no optical identification for the radio source down to the 4 m plate limit ($F \gtrsim 22.5$).

IV. DISCUSSION

In the two fields observed by *Einstein* in SA 68, four X-ray sources were found inside the ribs, and in SA 57 and UMi only one X-ray source was found. Thus the complete sample given in Table 2 consists only

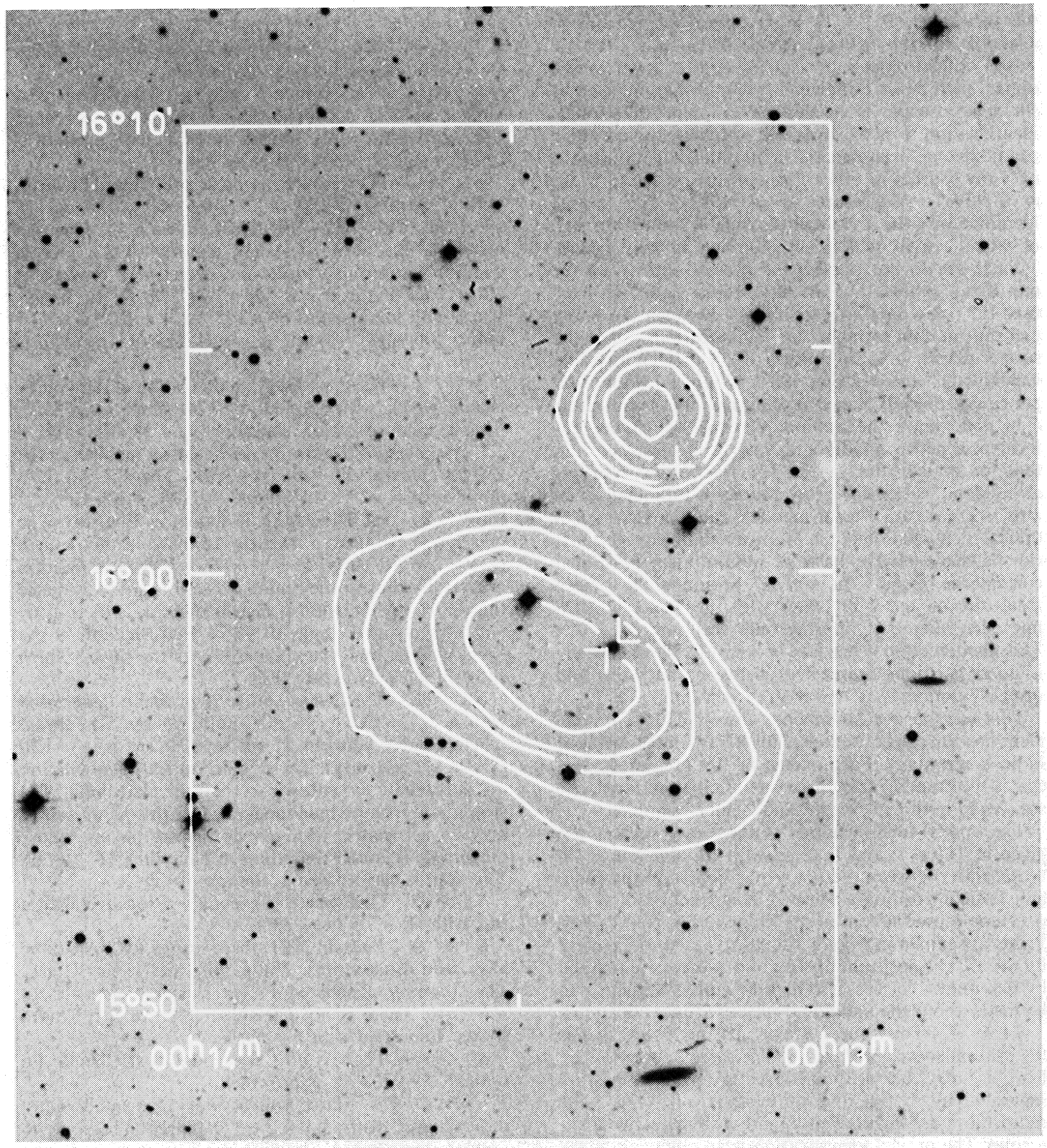

FIG. 1.—Radio X-ray sources in SA 68 superposed on a reproduction of the red print of the Palomar Sky Survey. The isointensity X-ray contours have been obtained by smoothing the raw image with a 2′ Gaussian. The extended bottom X-ray source is SA 68 A. It is associated with the elliptical galaxy ($z = 0.083$) between the two tick marks and the double radius source ($S_{21} = 6.0$ mJy) whose lobes are at the location of the two tick marks. The top X-ray source is SA 68 E which is associated with a $S_{21} = 63.6$ mJy radio source whose location is marked by the cross. It has no optical identification down to the 4 m red plate limit ($F \gtrsim 22.5$).

of five sources. Another five sources are added if the "outer" sample is considered. Clearly the X-ray surveys described here do not penetrate as far in space as the optical and radio surveys of the same sky areas. We cannot derive any profound cosmological conclusion from our limited X-ray sample but can compare our results with those of previous medium sensitivity surveys such as that of M.

We first discuss the number-intensity distribution. From the source counts of Maccacaro *et al.* (1982), 3.8 sources with fluxes greater than 11.4×10^{-14} ergs cm^{-2} s^{-1} are expected in the SA 68 solid angle of 0.73 square degrees. We find four sources. In the total solid angle of 0.78 square degrees of SA 57, 0.9 source would be expected. We find one source. Thus our results are entirely consistent with the $\log N(>S)$–$\log S$ relationship derived by M who found a slope of -1.53 ± 0.16 and a normalization factor of 2.7×10^{-16} (with S in ergs cm^{-2} s^{-1} and N in number of sources per steradian).

We now discuss the statistics of our identifications. Maccacaro *et al.* (1982) found in their intermediate sensitivity surveys, also at high galactic latitudes, that about 25% of the X-ray sources can be identified with galactic stars. Applying this percentage to both our "inner" and "outer" X-ray sample gives two objects which accounts nicely for the two proposed stellar identifications in Tables 2 and 3. Consequently, we shall base the following discussion on the assumption that, among the eight remaining X-ray sources, those which do not possess an optical identification are extragalactic objects. A further check on the validity of our identifications comes from the X-ray visual flux ratio S_x/S_v for our sources. These ratios are listed in Tables 2 and 3. Their values are fully consistent with the proposed identifications. Galactic stars have S_x/S_v less than 0.001 (except for late-type K and M stars), while extragalactic objects (cluster galaxies and QSOs) have S_x/S_v varying between 0.1 and 100 (M).

The fraction of extragalactic X-ray sources in our sample which are detected in the radio is high: possibly as many as three out of four, but probably at least four out of eight if source SA 68 E is not counted. As pointed out by Feigelson, Maccacaro, and Zamorani (1982), the radio detection rate of the X-ray sample depends primarily on the distribution of α_{rx}, the radio/X-ray spectral index, through the smallest detectable value of α_{rx} for a particular set of observations. For our sample, the limiting value of α_{rx} is ~ 0.59. From the α_{rx} distribution derived by Feigelson, Maccacaro, and Zamorani (1982), we would predict a radio detection rate of our X-ray sample of $40\% \pm 15\%$, which is in reasonable agreement with our results. This radio detection rate is very comparable to that of $\sim 35\%$ obtained by Feigelson, Maccacaro, and Zamorani (1982) who observed the *Einstein* medium sensitivity sources with the VLA down to a limiting sensitivity of ~ 1 mJy. This is to be expected since the radio and X-ray sensitivities of our survey and that of the Maccacaro group are very similar, the α_{rx} of the latter group being ~ 0.55. The much lower radio detection rates ($\sim 15\%$) of the *Einstein* deep surveys (Giacconi *et al.* 1979) result mainly from the lower (by a factor of ~ 8) X-ray limit of these surveys, the radio limit being essentially the same (~ 1 mJy). The radio/X-ray slopes are steeper, being ~ 0.75 as compared to ~ 0.55.

We now use the statistics of the *Einstein* intermediate sensitivity survey to discuss the nature of the extragalactic objects in our sample. There are three broad categories of extragalactic objects which emit X-rays: active galactic nuclei (AGNs) which include QSOs, Seyfert galaxies, or BL Lac objects; normal nonactive galaxies (i.e., without non thermal optical emission); and clusters of galaxies. In the *Einstein Observatory* medium sensitivity survey, $\sim 75\%$ of the extragalactic X-ray sources are associated with AGNs, while the remaining 25% are associated with clusters of galaxies (20%) or normal galaxies (5%).

The radio detection rate at 6 cm of the X-ray AGNs is $\sim 28\%$, and that for the cluster and normal galaxies is $\sim 50\%$ (Feigelson, Maccacaro, and Zamorani 1982). Of the X-ray sources that are not detected in the radio, about 80% are associated with an AGN. Thus it is most likely that source SA 68 B in Table 2 is associated with an AGN, as is source SA 68 H in Table 3. Similarly, since about two out of three of the radio-detected X-ray sources in the medium sensitivity survey are associated with an AGN, at least one of the sources SA 68 F and UMi A, and possibly both, are associated with an AGN. This gives a probable identification rate with AGNs of four $(1 + \frac{4}{5} + \frac{4}{5} + \frac{2}{3} + \frac{2}{3})$ out of eight (50%), and hence also four out of eight (50%) with clusters or normal galaxies without active nuclei. Of course, the preceding estimates assume that the statistics for the *Einstein* medium sensitivity survey apply to the present survey, which may not be rigorously true. For example, we have not explicitly taken into account the difference in radio wavelengths of the present survey (21 cm) and of the survey by Feigelson, Maccacaro, and Zamorani (1982) (6 cm). The radio detection rate for a sample of X-ray sources with a fixed composition of AGNs and clusters of normal galaxies depends on radio frequency and detection limit. For an almost identical radio detection limit of ~ 1–2 mJy at 6 and 21 cm, one might expect to detect relatively more AGNs at 6 cm than at 21 cm because of the difference in radio spectrum of the two classes of objects. Thus our estimate of the fraction of AGNs in our X-ray sample may be an overestimate. We shall consider it as an upper limit.

Our estimate ($\lesssim 50\%^{+40\%}_{-24\%}$) of the fraction of AGNs in a complete X-ray sample at medium sensitivity is consistent with that found by M ($\sim 75\% \pm 13\%$) in their survey. This is an interesting result given the fact that the two medium sensitivity samples have been selected by completely different methods. Our fields have not been preselected for the presence or absence of certain types of objects. In contrast, a considerable fraction (more than one-third) of the X-ray data used by M come from IPC frames centered on previously known X-ray QSOs. Also, all observations centered on nearby Abell clusters

1983ApJ...275....1K

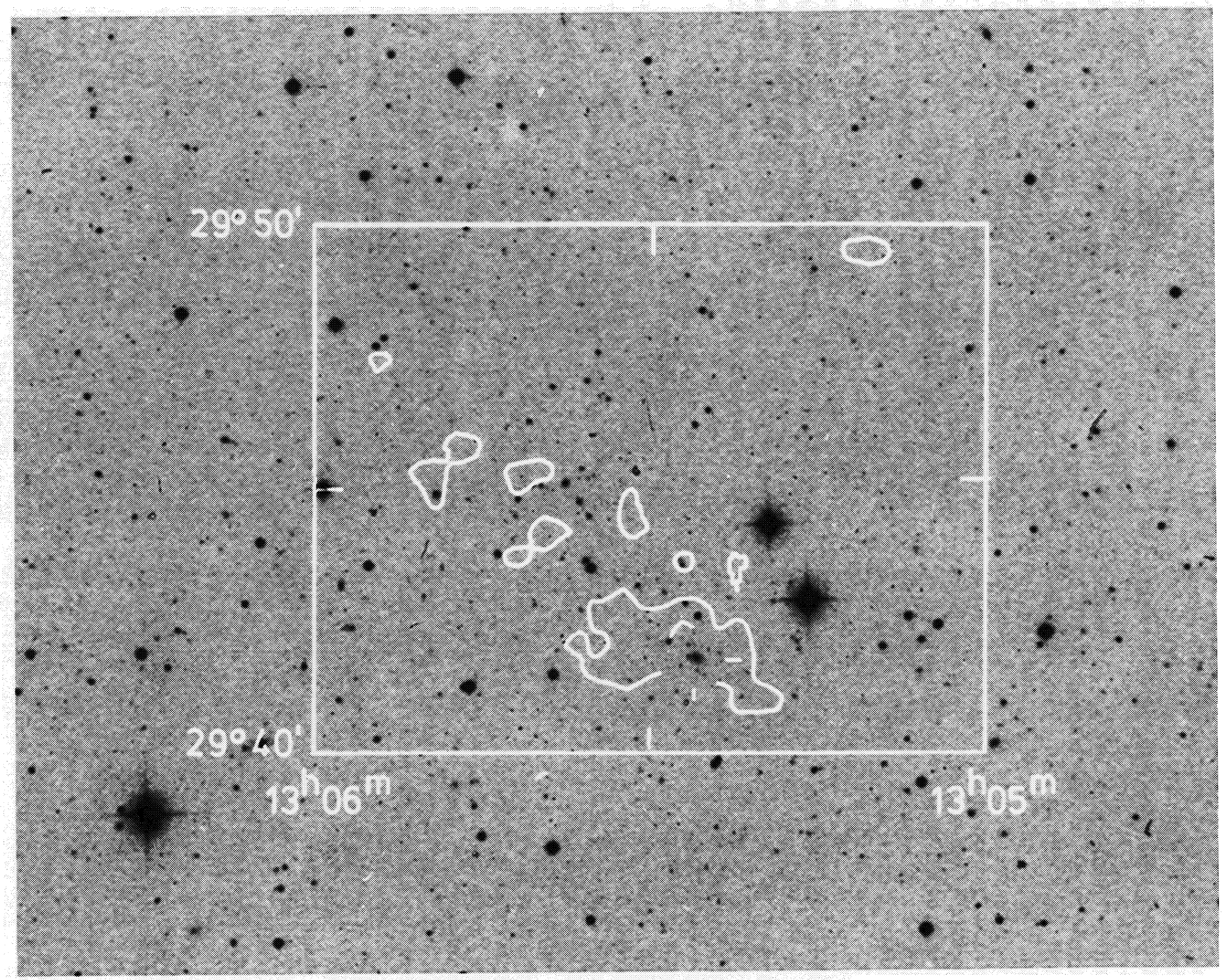

FIG. 2.—Radio X-ray source is SA 57 superposed on a reproduction of the red print of the Palomar Sky Survey. The isointensity X-ray contours have been obtained from the raw image without smoothing. The peak of the X-ray emission coincides with the giant elliptical galaxy in the Zwicky cluster Zw 1305.4+2941 at $z = 0.241$. This galaxy is also a radio source with $S_{21} = 2.4$ mJy. The position of the radio source is given by the two tick marks. The X-ray emission appears extended in the same direction (position angle ~45°) as that of the cluster of galaxies which has a linear structure.

of galaxies ($D \leq 3$) have been excluded from the M sample.

In summary, we have observed with the Imaging Proportional Counter of the *Einstein Observatory* several fields in SA 57, SA 68, and UMi which possess deep optical ($B_{\rm lim} \sim 23$ mag) and radio ($S_{21} \sim 1$ mJy) coverage. The X-ray sensitivity reached in our survey is $\sim 2 \times 10^{-13}$ ergs cm^{-2} s^{-1} (5 σ limit), which is comparable to that of the *Einstein* medium sensitivity survey of serendipitous X-ray sources (M), but about a factor of 8 higher than the deep surveys of Giacconi *et al.* (1979). The number of X-ray sources detected above our flux limit is entirely consistent with the $\log N(>S)$–$\log S$ slope of ~ -1.5 derived by M. Because of the lack of the spectroscopic information, we have used the radio data as intermediary between the X-ray and optical data to make our identifications. We find that as many as 50%–75% of our extragalactic X-ray sources are detected in radio, in agreement with the results of the VLA 6 cm observations by Feigelson, Maccacaro, and Zamorani (1982) of the X-ray sources detected in the *Einstein* medium sensitivity survey. The derived fractions of AGNs and of clusters/normal galaxies are also consistent with those found in the *Einstein* medium sensitivity survey.

We thank Drs. Richard Kron and David Koo for letting us use their 4 m plate material, and Dr. Tommaso Maccacaro for constructive comments on the manuscript. T. X. T. acknowledges partial financial support from NASA contract NAS8-33327 and NSF grant 81-19683. The Westerbork Radio Synthesis Telescope is administered by the Netherlands Foundation for Radio Astronomy with financial support from Z.W.O. R. A. W. acknowledges travel support from the NATO Scientific Affairs Division, grant 1479.

REFERENCES

Feigelson, E. D., Maccacaro, T., and Zamorani, G. 1982, *Ap. J.*, **255**, 392.
Giacconi, R., *et al.* 1979, *Ap. J.* (*Letters*), **234**, L1.
Griffiths, R. E., Maccacaro, T., Murray, S. S., and Giacconi, R. 1981, in *X-ray Astronomy*, ed. R. D. Andresen (Dordrecht: Reidel), p. 67 (*Space Sci. Rev.*, **30**, 67).
Kron, R. G. 1980, *Ap. J. Suppl.*, **43**, 305.
Maccacaro, T., *et al.* 1982, *Ap. J.*, **253**, 504 (M).
White, S. D. M., Silk, J., and Henry, J. P. 1981, *Ap. J.* (*Letters*), **251**, L65.
Windhorst, R. A., van Heerde, G., and Katgert, P. 1983, *Astr. Ap. Suppl.*, submitted.

P. Katgert and R. A. Windhorst: Sterrewacht, Postbus 9513, 2300 RA Leiden, The Netherlands

Trinh X. Thuan: Astronomy Department, University of Virginia, P.O. Box 3818, University Station, Charlottesville, VA 22903