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OBSERVATIONS OF THE X-RAY SOURCES IN THE NEARBY Sc GALAXY M33

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ABSTRACT

Two observations of the Local Group spiral M33 with the Imaging Proportional Counter (IPC) on the *Einstein* Observatory reveal the presence of 11 point sources which, if at the distance of M33, have X-ray luminosities ranging from 10^{37} ergs s^{-1} to 10^{39} ergs s^{-1}. The brightest source, coincident with the nucleus of the galaxy, comprises approximately 70% of the total X-ray luminosity of the galaxy. If this source is a single source, it must be qualitatively different from the compact binary sources which dominate the X-ray luminosity of our Galaxy.

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

I. INTRODUCTION

The Local Group Sc galaxy M33 (=NGC 598) is an ideal galaxy to study the X-ray properties of late-type spiral systems because of its proximity (720 kpc), low angle of inclination, and well-defined, open spiral arms. At optical wavelengths, Population I components, including H II regions, OB associations, supernova remnants, luminous blue and red supergiants, and variable stars have been studied. At radio wavelengths, surveys of continuum sources at 1415 MHz (Israel and van der Kruit 1974) and of 21 cm emission (Newton 1980) have been completed. In this *Letter*, we discuss X-ray observations of M33 using the Imaging Proportional Counter (IPC) on the *Einstein* Observatory. Prior to these observations, M33 had not been detected as an X-ray source.

II. THE EXPERIMENT AND THE OBSERVATIONS

The *Einstein* Observatory is an X-ray telescope which, with the IPC in the focal plane, can be used to position sources emitting X-rays in the energy range 0.15–4.5 keV to an accuracy of 40″(1 σ) (Giacconi *et al.* 1979). The observatory was used to image M33 during two periods, the first lasting from 20^h 1979 July 31 to 16^h 1979 August 3 (UT) and the second from 6^h 1980 January 11 to 1980 January 12 (UT). A total of 22,402 and 12,216 s of useful data were obtained in the two observations. The instrument performed normally except for a commanded decrease in the high voltage of the IPC, which resulted in a marked gain change in the instrument between the beginning and the end of the first set of observations.

Six bright sources are visible in the combined image, along with several other features whose statistical significance is not immediately apparent from the contour plot shown in Figure 1. The extents of all the bright sources are consistent with the point source response function of the IPC. To locate the weaker sources in the image, we have considered three sets of data, corresponding to the high-gain (8432 s) and low-gain (13,970 s) portions of the first observing period and the entire second observation, independently. We first applied the standard IPC point source detection algorithm to establish a list of possible point sources to each data set. This algorithm isolates portions of the image in which the flux is significantly greater than the global background rate. This algorithm serves as a useful tool for positioning candidate point sources but cannot be used indiscriminantly, particularly on long exposure fields, because the assumption of a uniform background is inadequate. Therefore, we have used a supplemental program to calculate the statistical significance of the candidate sources. The supplemental algorithm establishes a local measure of the background by finding the count rate within an annulus centered on the candidate source position having inner and outer radii of 180″ and 320″, excluding regions of the annulus falling near the window support ribs of the IPC or other point sources. The source strength is derived from the excess count rate in those pixels within 128″ of the source centroid. The algorithm minimizes the effect of gain changes by utilizing data only in those pulse height channels which nominally correspond to the

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energy range 0.15–4.5 keV. Additionally, the algorithm characterizes the spectrum of the source in terms of a hardness parameter $(H - S)/(H + S)$, where S and H are the source count rates in the pulse height ranges corresponding to the energies between 0.15–1.5 keV and 1.5–4.5 keV, respectively.

A list of the 11 point sources detected at a confidence level of at least 3 σ is presented in Table 1. Each of these sources can be identified with an isolated feature in the contour plot. The parameters listed in the table columns are, respectively: (1) the source number, (2)–(3) the source position, (4)–(6) the source strengths in counts s^{-1} in each of the data sets, (7) the mean source strength, (8) the mean hardness parameter, and (9) the average 0.15–4.5 keV luminosity of the source. The error in the hardness parameter is dominated by systematic effects for the stronger sources, primarily owing to changes in the gain as a function of time and position in the detector. We have estimated this systematic error to be ± 0.2, based on the root mean square deviation of the hardness parameters of the sources in the three data sets. For the luminosity calculation, we have assumed that the source spectra are reasonably well described in terms of a power law with photon index equal to -2. We have corrected the luminosities for intervening absorption equivalent to a cosmic abundance gas with a hydrogen column density of 10^{21} cm^{-2}. This value is equal to the galactic 21 cm column density in the direction of M33 plus half of the average column density in M33 itself (Heiles 1975; Newton 1980). The expected hardness ratio from such a spectrum is $+0.1$, equal to the measured hardness parameter of the dominant source in M33, but somewhat greater than the average hardness parameter -0.1. (To obtain a hardness ratio of -0.1 with the same absorption column density, we would have required a spectrum with index equal to -2.5, and the derived luminosities would have been about a factor of 1.5 higher because a greater proportion of the 0.15–4.5 keV X-rays would have been absorbed by the intervening matter.) The luminosities of the detected sources range over approximately two orders of magnitude, from 9.8×10^{36} ergs s^{-1} to 1.1×10^{39} ergs s^{-1} (assuming that all but source 11 are located in M33).

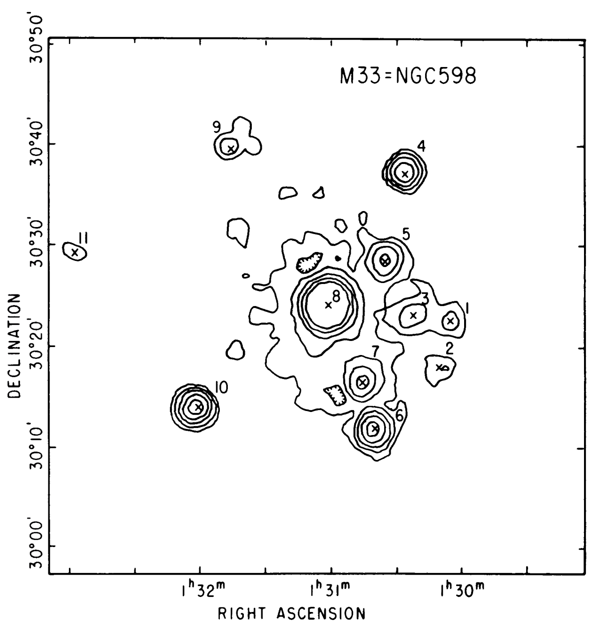

Fig. 1.—A contour of the combined M33 image obtained with the IPC. Background rate in the detector decreases away from the center of the field, owing to vignetting. The contour plot is not corrected for these effects, which make a source at the edge appear somewhat fainter than the same source at the center of the field. Positions of point sources are indicated. The contour levels in the plot correspond to 0.0005, 0.00075, 0.001, 0.00125, and 0.0015 counts $s^{-1}(')$, respectively.

In an attempt to identify the point sources in M33, we have examined photographic plates of M33 obtained in the red, visual, and UV bands at the Cassegrain focus of the Asiago 1.82 m reflector (original scale 12″ mm^{-1}) as well as Hα and [S II] interference filter plates obtained at the Palomar 48 inch (1.2 m) telescope (see Fig. 2 [Pl. L4]) We also checked to see whether any of the X-ray source positions corresponded to sources in the lists of H II regions by Boulesteix *et al.* (1974), star clusters by

TABLE 1

X-Ray Sources in the M33 Field

Source Number (1)	Right Ascension (1950) (2)	Declination (1950) (3)	Source Strength: Set 1 (10^{-3} cts s^{-1}) (4)	Set 2 (10^{-3} cts s^{-1}) (5)	Set 3 (10^{-3} cts s^{-1}) (6)	Mean Source Strength (10^{-3} cts s^{-1}) (7)	Hardness Parameter (8)	L_x (ergs s^{-1}) (9)
1..........	1h30m 6s.0	30°22′31″	5.0±1.3	7.4±1.1	5.2±1.3	6.0±0.7	0.0	1.7 (37)
2..........	1 30 10.7	30 18 00	2.3±1.3	3.7±1.1	4.0±1.2	3.4±0.7	−0.1	9.8 (36)
3..........	1 30 22.6	30 23 09	7.1±1.9	4.0±1.3	3.6±1.4	4.5±0.9	−0.7	1.3 (37)
4..........	1 30 26.3	30 37 12	23.6±2.0	22.4±1.6	20.8±1.6	22.0±1.0	+0.1	6.4 (37)
5..........	1 30 35.1	30 28 29	15.4±1.9	12.6±1.6	14.5±1.6	14.0±1.0	+0.1	4.0 (37)
6..........	1 30 40.8	30 11 57	40.9±2.6	33.5±1.9	33.4±2.0	34.5±0.8	0.0	9.9 (37)
7..........	1 30 46.1	30 16 38	23.6±2.4	14.0±1.6	12.0±1.6	14.9±1.0	−0.1	4.3 (37)
8..........	1 31 01.7	30 24 03	394.5±6.9	379.7±5.4	361.0±5.6	376.4±3.4	+0.1	1.1 (39)
9..........	1 31 46.8	30 39 40	4.5±1.3	5.0±1.1	5.4±1.2	5.0±0.7	−0.2	1.4 (37)
10.........	1 32 01.9	30 14 03	36.6±2.3	32.8±1.8	33.4±2.0	34.0±1.2	−0.2	9.8 (37)
11.........	1 32 58.1	30 29 13	4.8±1.3	4.0±1.0	0.5±0.9	2.6±0.6	−0.6	[a]

[a] Probably a foreground star.

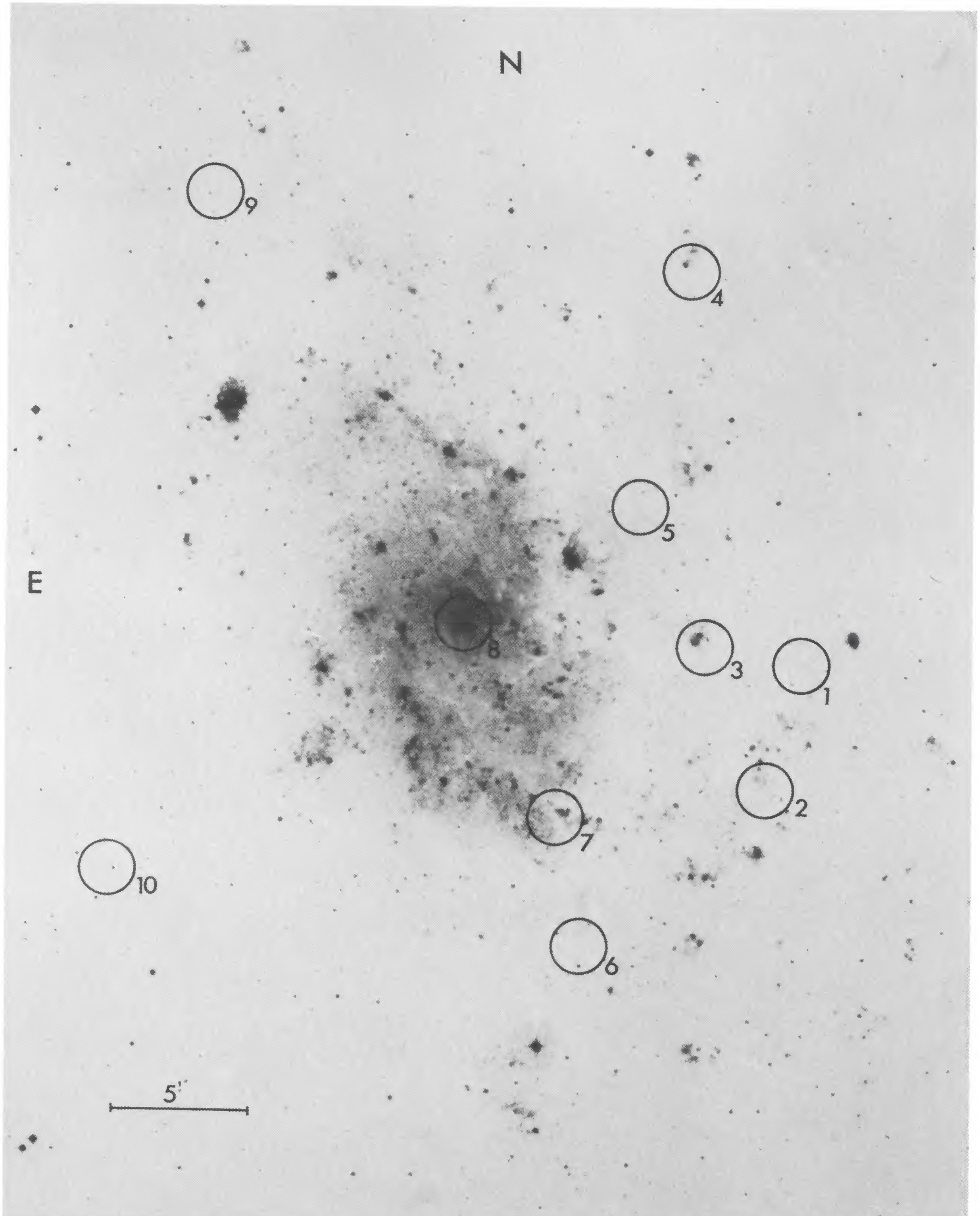

FIG. 2.—The positions of the 11 X-ray sources given in Table 1 are superposed on this photograph of M33 obtained with the Palomar Schmidt through an Hα interference filter. The circles, which are 2′ in diameter, correspond approximately to 90% confidence contour. Source 11 is outside the field.

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Melnick and D'Odorico (1978), and OB associations by Humphreys and Sandage (1980). Because of the limited spatial resolution of the IPC, all of the suggested identifications below should be regarded as tentative until confirmed with higher-resolution instruments.[2]

Source 1.—The X-ray source is located in the western extension of the main southern arm of the galaxy, close to the H II region 276 and within the OB association 25 by Humphreys and Sandage (1980). The X-ray source position is 90″ from the 5 mJy radio source B in the 21 cm continuum survey (Israel and van der Kruit 1974). The radio source has a nonthermal spectrum (Goss *et al.* 1980) with $\alpha = -0.45$ and no obvious optical counterpart.

Source 2.—There is no obvious optical or radio counterpart for this X-ray source, which is projected on the OB association 21 by Humphreys and Sandage (1980).

Source 3.—This weak and poorly defined X-ray source is apparently centered on the H II region NGC 592, the third brightest in M33. The two brighter H II regions, NGC 604 and NGC 595, were not detected. The X-ray spectrum of this source is the softest of all the sources in M33, which by analogy with the very soft spectra of SNRs in the Large Magellanic Cloud (Long and Helfand 1979), might lead one to suspect that this is a SNR. It was not, however, identified as a SNR by D'Odorico, Dopita, and Benvenuti (1980). The [O III]/Hα line intensity ratio from the nebula is normal for an H II region at that distance from the center of the galaxy (Searle 1971). It is a weak source in the 1415 MHz radio survey of Israel and van der Kruit (1974).

Source 4.—The source coincides with the H II region IC 133, which appears as two compact, intense knots to the south of the rich OB association (Humphreys and Sandage 1980) (see Fig. 3*a* [Pl. L5]). Spectra of the two blobs, obtained by PAC, using the image tube scanner on the 3 m telescope at Lick Observatory, show little stellar continuum and intense emission lines whose relative intensities strongly resemble those of nearby H II regions (see Smith 1975). IC 133 is a relatively intense radio source detected both at 1415 and 4850 MHz (von Kap-herr, Berkhuijsen, and Wielebinski 1978). Owing to limited spatial resolution, it is not possible to identify the radio or X-ray source with the bright optical knots. Part of the radio or optical emission may be due to a SNR which has a faint optical counterpart, but no such object is evident in the optical material obtained by D'Odorico *et al.*

Source 5.—There is no obvious optical or radio counterpart for this X-ray source.

Source 6.—This is the second strongest source in the field. It may be associated with a star cluster 20″ south of the X-ray position (13 in the list by Melnick and D'Odorico 1978) shown in Figure 3*b*.

Source 7.—The source, located in the southern spiral arm of M33, could possibly be associated with H II region 208 in the list compiled by Boulesteix *et al.* (1974) or association 13 of Humphreys and Sandage (1980). As shown in Figure 3*c*, the region is made up of several emission-line knots. None of these is very strong in [S II] as would be expected from a SNR. The count rate from this source varied by almost a factor of 2 between the first and second half of the observation in 1979 July/August, consistent with the hypothesis that it is a compact galactic X-ray source.

Source 8.—The strongest source in M33 emits approximately 70% of the total X-ray luminosity of the galaxy. The source is undoubtedly associated with the nuclear region of the galaxy, which is semistellar and rather inconspicuous at optical (Walker 1964) and radio wavelengths (Israel and van der Kruit 1974). The apparent displacement of the source centroid by 35″ from the nucleus is consistent with the positional accuracy of the IPC. The source is sufficiently bright that short-term (100 s) variations in the luminosity could be studied; none was observed. The impression that the nuclear emission is dominated by a single source, rather than a collection of sources of roughly equal intensity only loosely associated with the nucleus as in the case of M31 (Van Speybroeck *et al.* 1979), has been confirmed with the high-resolution imager aboard the *Einstein* Observatory, which has a resolution of $\sim$5″ (Markert 1980).

Source 9.—This source is within 20″ of the cluster 53 (Fig. 3*d*) in the list of Melnick and D'Odorico (1978).

Source 10.—Within the error circle of this relatively strong source outside the main body of the galaxy, there is a reddish foreground star ($m_v = 14.5$) and a small cluster of blue stars, fainter than $m_v \approx 18$. The *UBV* colors of the star are consistent with a spectral classification of F5. Coronal emission from a main-sequence or post-main-sequence F5 star cannot account for the observed X-ray emission because the inferred X-ray to optical luminosity ratio of 0.1 greatly exceeds the luminosity ratios observed in normal F stars of order 10^{-4}–10^{-5} (Vaiana *et al.* 1981).

Source 11.—This source is well removed from M33. There is no compelling reason to associate it with the galaxy. Its position is consistent with the HD star $+30°247$ ($m_v = 9.4$). The soft spectrum and the ratio of the X-ray to optical flux, 10^{-5}, would be appropriate if this is the correct identification. As a result, we have not included its luminosity in Table 1. It was not detected during the second observing period.

III. DISCUSSION

We have detected 11 sources of X-ray emission in or near the galaxy M33. These sources range in luminosity from 10^{37} to 10^{39} ergs s^{-1}. In a study of similar sensitivity of another more massive Local Group spiral, M31, Van Speybroeck *et al.* (1979) reported the detection of 69 sources. In our own Galaxy, the effects of absorption in the galactic plane limit the completeness of surveys below 2 keV. In the energy range 2–11 keV, however, 26 sources exist, to a completeness limit of 5×10^{36} ergs s^{-1} (Clark *et al.* 1978). While some caution should be exercised in comparing results in different energy windows, the relative numbers of sources in M33, the Galaxy, and M31 certainly appear to be consistent with the ratio of the masses of the galaxies (3.9 ×

[2] In particular, several of the sources may not be associated with M33. The expected number of serendipitous sources brighter than 0.004 counts s^{-1} is approximately 1.5. Most of these sources are foreground stars or background quasars.

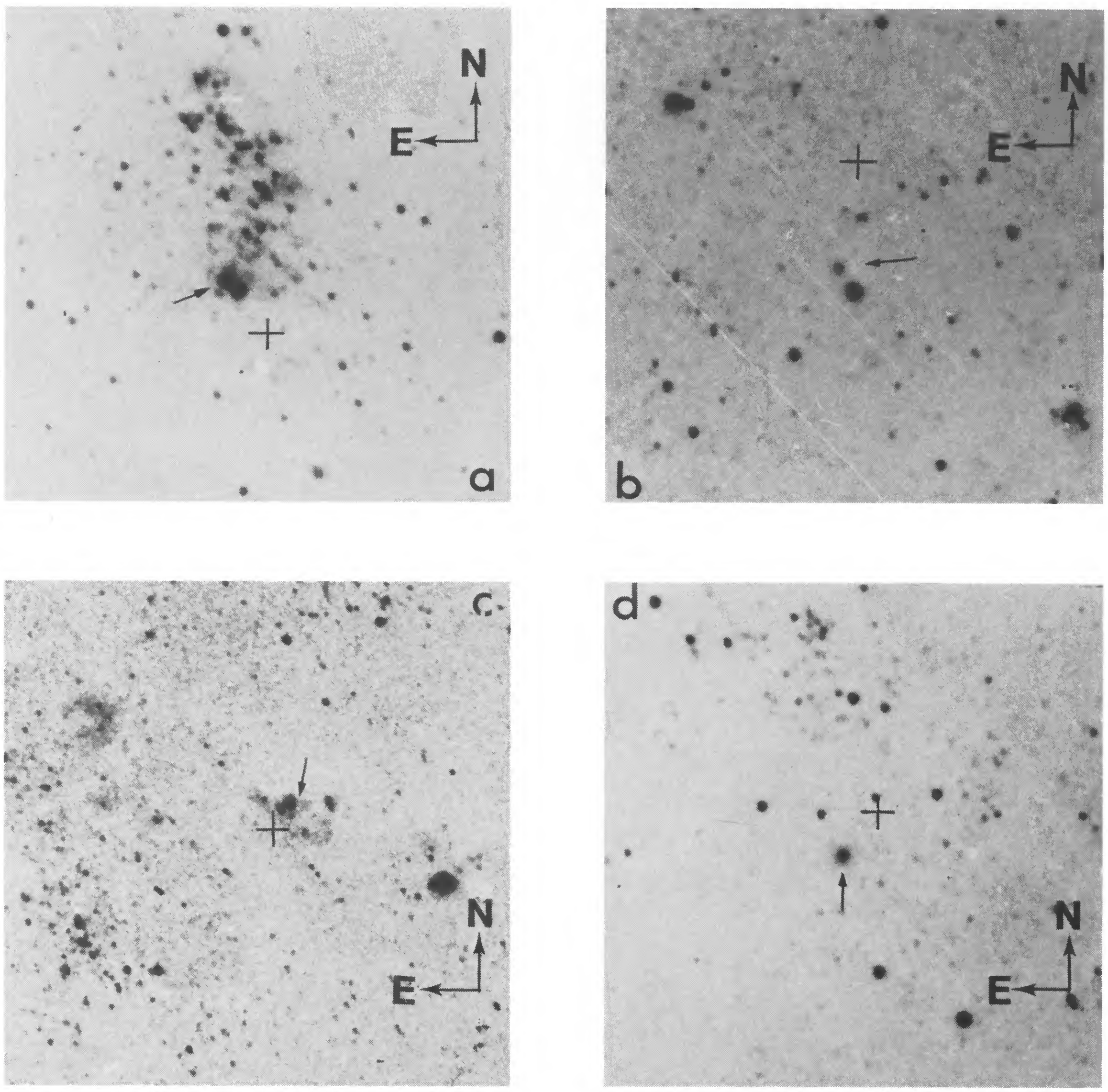

FIG. 3.—Finding charts for the X-ray sources 4, 6, 7, and 10. They are from a Palomar 1.5 m telescope, IIIa-J + GG385 plate by Melnick (*a*), (*b*), (*d*) and from a 1.82 m Asiago telescope, 103a-E + RG1 plate (*c*). Crosses are centered on the positions of Table 1; arrows point to the optical identifications suggested in the text. The field is 3′ × 3′, with north to the top, east to the left.

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10^{10} $m_\odot$, 1.3×10^{11} $m_\odot$, and 3.1×10^{11} $m_\odot$, [van den Bergh 1975]).

Unlike M31 and the Galaxy, however, the X-ray luminosity of M33 is dominated by a single source. The luminosity of this source is considerably greater than that of a single, compact, galactic X-ray source, and therefore it seems likely that the X-ray emission mechanism is connected intimately with its location in the galactic nucleus. Possibly the nuclear source in M33 is simply a low-luminosity example of the type of activity which occurs in active galaxies. The nucleus is very compact, smaller than a typical globular cluster and, unlike the nuclei of M31 and M32, does not merge with the surrounding regions. Unlike typical active galaxies however, (*a*) the nucleus of M33 is a very weak radio source; (*b*) the velocity dispersion of the nucleus is very low—less than 30 km s^{-1} (Gallagher 1980; Walker 1964)—and (*c*) the nucleus of M33 does not show Hα in emission. Its color is very blue compared to most galaxies, probably indicating high metallicity (McClure, Cowley, and Compton 1980) or relatively recent star formation (van den Bergh 1976). Should the latter turn out to be correct, it might be possible to account for the X-ray emission from M33 in terms of a number (~10) of compact X-ray sources in the nucleus itself.

Most of the other sources in M33 are located well away from the nucleus at distances of 1.5–5 kpc. Many of these can be associated with individual H I features or other Population I markers, similar to the source population coincident with the dominant Population I feature in M31, the H I ring (Van Speybroeck *et al.* 1979). In M33, only two sources, 10 and 11, lie outside the main body of H I (Newton 1980), and at least one of these, 11, is likely to be unassociated with the Galaxy.

The X-ray sources do not correspond to optically identified SNRs in M33 in contrast to the Large Magellanic Cloud (LMC) where SNRs contribute a significant portion of the total X-ray luminosity (Long, Helfand, and Grabelsky 1981). The radii of SNRs in M33 and the LMC are comparable, so that optically identified SNRs in the two galaxies should have similar X-ray luminosities. However, most LMC remnants would not be detected at the greater distance of M33, as simply scaling the count rates of LMC remnants indicates. In addition, the X-ray spectra of shell-like SNRs, which are dominated by low-energy X-rays ($\lesssim$0.5 keV), are strongly affected by interstellar absorption. H I column densities within M33 (Newton 1980) tend to exceed column densities in the LMC and, as a result, even a remnant as bright as N132D might have been missed.

What then are the nonnuclear sources in M33. Some may be young Crab-like SNRs since such SNRs would not have been identified on the basis of [S II] photographs. The majority, however, are probably compact objects in mass-transferring binary systems. No other source population in our Galaxy exhibits a similar luminosity range. The most characteristic signature of a compact source, time variability, is evident in the count rate of one source, 7. If the others are also compact binaries, future studies should reveal time variations in their X-ray output as well.

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REFERENCES

Boulesteix, J., Courtes, G., Laval, A., Monnet, G., and Petit, H. 1974, *Astr. Ap.*, **37**, 33.
Clark, G., Doxsey, R., Li, F., Jernigan, J. G., and van Paradijs, J. 1978, *Ap. J.* (*Letters*), **221**, L37.
D'Odorico, S., Dopita, M. A., and Benvenuti, P. 1980, *Astr. Ap. Suppl.*, **40**, 67.
Gallagher, J. S. 1980, private communication.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Goss, W. M., Ekers, R. D., Danziger, I. J., and Israel, F. P. 1980, *M.N.R.A.S.*, **193**, 901.
Heiles, C. 1975, *Astr. Ap.*, **20**, 37.
Humphreys, R., and Sandage, A. 1980, *Ap. J. Suppl.*, **44**, 319.
Israel, F., and van der Kruit, P. C. 1974, *Astr. Ap.*, **32**, 363.
Long, K. S., and Helfand, D. J. 1979, *Ap. J.* (*Letters*), **234**, 277.
Long, K. S., Helfand, D. J., and Grabelsky, D. 1981, *Ap. J.*, **248**, in press.
Markert, T. 1980, private communication.
McClure, R. D., Cowley, A. P., and Compton, D. 1980, *Ap. J.*, **236**, 112.
Melnick, J., and D'Odorico, S. 1978, *Astr. Ap. Suppl.*, **39**, 249.
Newton, K. 1980, *M.N.R.A.S.*, **190**, 689.
Searle, L. 1971, *Ap. J.*, **168**, 327.
Smith, H. E. 1975, *Ap. J.*, **199**, 205.
Vaiana, G. S., *et al.* 1981, *Ap. J.*, submitted.
van den Bergh, S., 1975, *Ann. Rev. Astr. Ap.*, **13**, 219.
———. 1976, *Ap. J.*, **203**, 764.
Van Speybroeck, L., *et al.* 1979, *Ap. J.* (*Letters*), **239**, L45.
Von Kap-herr, A., Berkhuijsen, E. M., and Wielebinski, R. 1978, *Astr. Ap.*, **62**, 51.
Walker, M. F. 1964, *A.J.*, **69**, 744.

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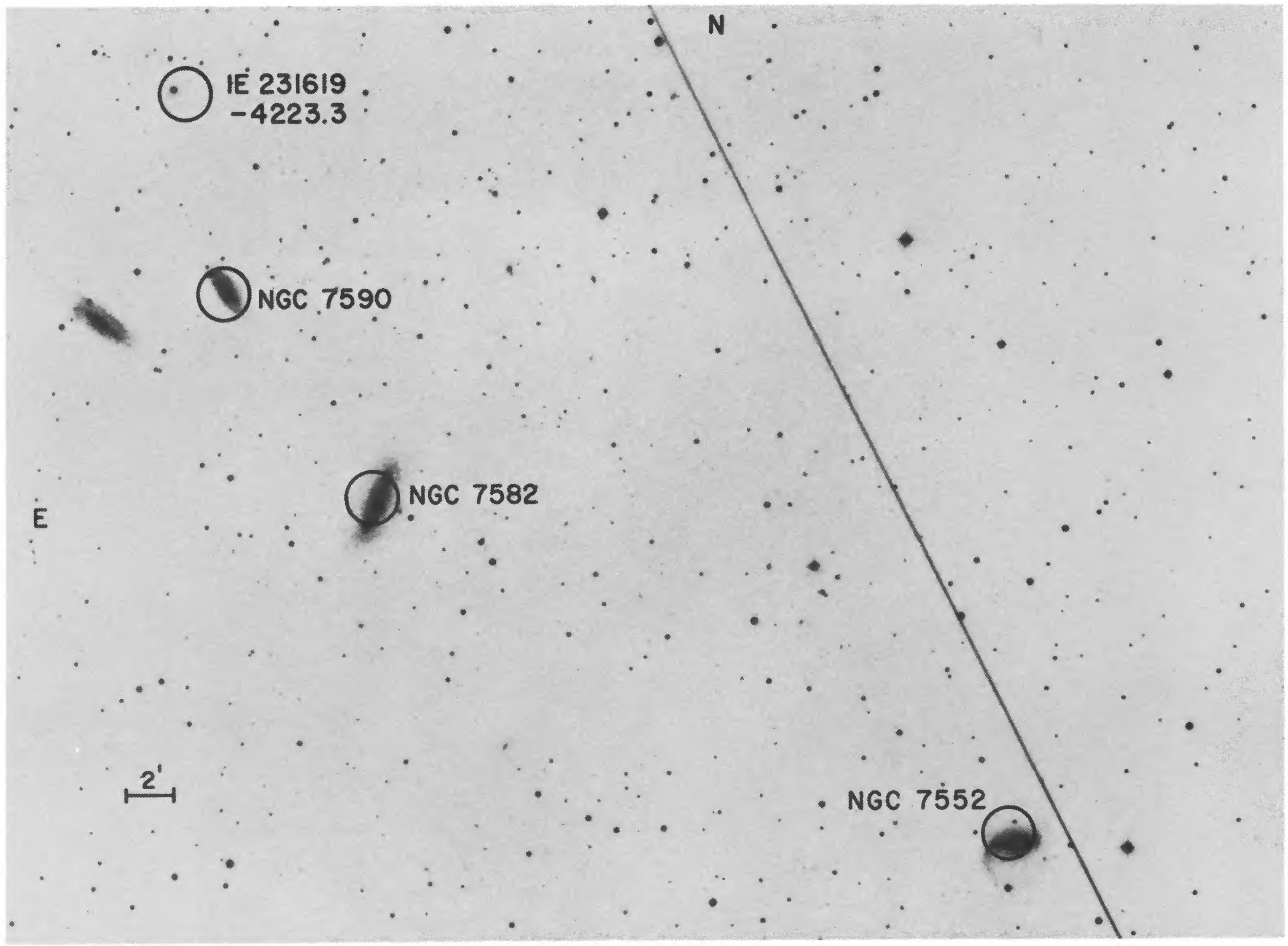

FIG. 1.—The position of the 4 sources in Table 1 plotted on a reproduction of the Palomar Sky Survey print (southern extension, courtesy National Geographic). The 90% confidence error circles are 1′ in radius.

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