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OBSERVATIONS OF X-RAY SOURCES IN M31

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ABSTRACT

We have observed 69 unresolved X-ray sources and seven diffuse or confused source regions in M31 with the *Einstein* Observatory. The typical limiting sensitivities in the 0.5–4.5 keV band were 9×10^{36} ergs s^{-1}. There are 21 sources in a compact inner bulge, seven globular clusters, 40 sources we categorize as Population I, and 8 sources near globular clusters but with position errors large enough so that four chance coincidences would be expected. The Population I sources are associated with bright visible objects, and with neutral hydrogen, dust, and other Population I tracers. Luminosity distributions of these classes are given. The nucleus of M31 is coincident with a 10^{38} ergs s^{-1} X-ray source at approximately the 90% confidence level.

Subject headings: clusters: globular — galaxies: stellar content — X-rays: sources

I. INTRODUCTION

The nearby galaxy M31 provides certain advantages for the study of typical galactic phenomena. The distances are known and absolute luminosities can be determined. The morphology is more apparent than that of our own Galaxy, and consequently the significance of source positions can be more easily understood. Perhaps more important, M31 is not exactly like our own Galaxy, and thus permits us to begin to study the correlation between galactic type and the characteristics of X-ray sources. These of course are familiar advantages, and in fact M31 was the first external galaxy to be studied with an optical telescope (Marius, 1612 December 15), and also the first to be studied in radio (inconclusively, by Reber, 1939 October 11; Reber 1940; however, see also van der Kruit and Allen 1976). It has been detected previously as an aggregate source in X-rays; for example, it is listed in the 4th *Uhuru* catalog by Forman *et al.* (1978) and in the *Ariel* catalog by Cooke *et al.* (1978), and was detected in soft X-rays by Margon *et al.* (1974). The *Einstein* Observatory provides for the first time adequate sensitivity and angular resolution to study individual X-ray sources in this galaxy.

We used the *Einstein* Observatory (Giacconi *et al.* 1979) on 1979 January 11–14 to study three fields in M31 with the imaging proportional counter detector (IPC), and one field with the high-resolution imaging detector (HRI). Preliminary results from two of the IPC fields and the HRI field are reported here.

II. OBSERVATIONS

The field centers, observation times, and typical limiting sensitivities are given in Table 1. The central IPC field is illustrated in Figure 1 (Plate L11). The field consists of approximately 20 identifiable sources in addition to a large, confused region near the center of the field. This region is resolved into about 45 individual sources in the HRI data. The center of the HRI field is shown in Figure 2 (Plate L12). The source near the nucleus and a source near our detection threshold are indicated. The northeast field, which is not shown, contains four obvious sources.

In almost all cases, the individual sources were identified using the standard *Einstein* data reduction programs, which are based upon a sliding acceptance box algorithm. The photons associated with each source were then used to estimate its position and luminosity. The typical systematic position errors are about 2″ and 1′ for the HRI and IPC, respectively. Statistical fluctuations also contribute to the position errors of the faint sources. All values of luminosities given in Table 1 and throughout this *Letter* refer to the 0.5–4.5 keV interval, which is the band normally observed with the *Einstein* IPC. Unfortunately, the IPC was operated at an anomalously high gain during these observations, which resulted in the unusually narrow energy acceptance bands given in Table 1. We choose to quote luminosities in the wider interval of 0.5–4.5 keV because most X-ray sources emit over a wide energy band, and we believe that stating luminosities for the anomalously narrow energy intervals observed is misleading, and that the use of the wider interval will facilitate a comparison of these data with other *Einstein* observations. The data associated with each IPC source were fitted to power-law and thermal bremsstrahlung models to determine spectral parameters. We estimated luminosities based upon the best-fit spectral parameters in those cases which were sensitive to these quantities. Typically, however, the models were not sensitive to the spectral parameters because of the low counting rates and the narrow acceptance bands; in these cases we estimated luminosities assuming a 5 keV thermal bremsstrahlung, or an energy index of -2, the results of the two models differing by only a few percent. All luminosities were corrected for absorption in our Galaxy corresponding to $N_H = 8 \times 10^{20}$ cm^{-2}; Margon *et al.* (1974) observed values of N_H between 6.1×10^{20} and

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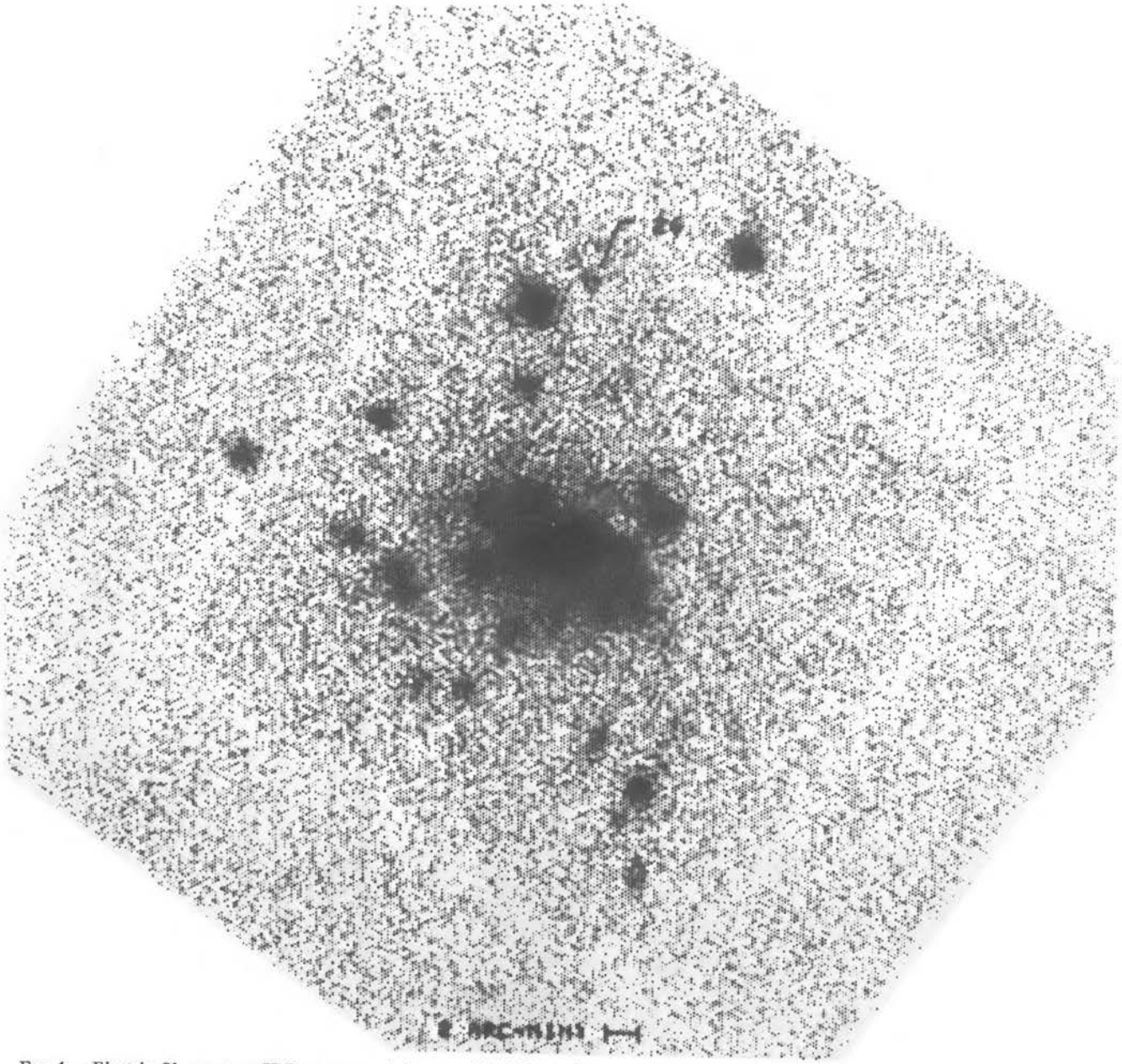


FIG. 1.—*Einstein* Observatory IPC exposure of the central field in M31. North is at the top and east is at the left. Source 26, which is indicated, is near the detection threshold. The nuclear region is unresolved.

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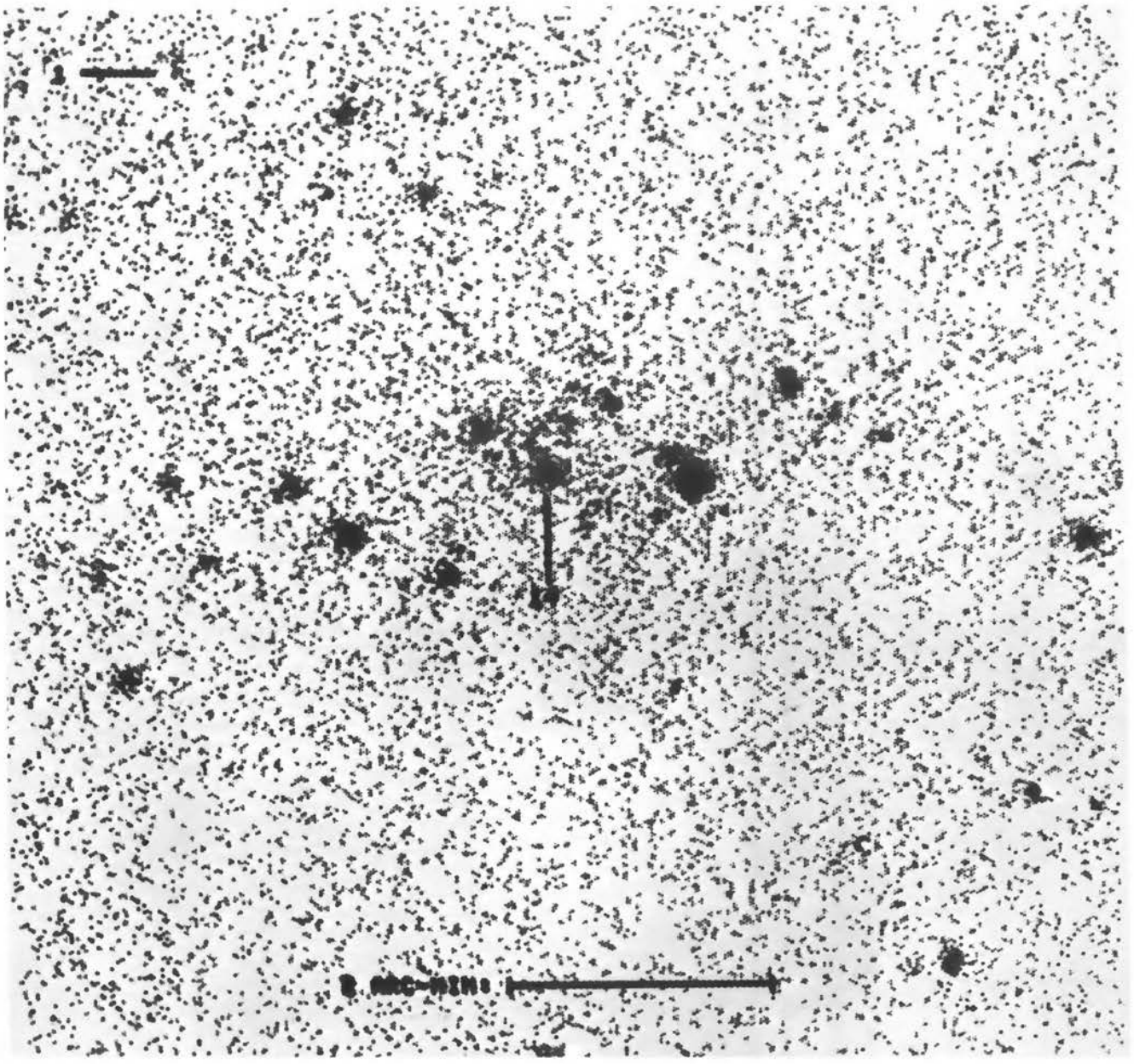


FIG. 2.—*Einstein* Observatory HRI exposure of the center of M31. North is at the top, and east at the left. Source 1, which is indicated, is near the detection threshold. The nucleus of M31 is coincident with source 14 within our measurement accuracy. The sources classified as the inner-bulge group are contained within 2′ of the nucleus.

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TABLE 1

Einstein OBSERVATIONS OF M31

Sequence	574	575	579
Instrument	IPC	IPC	HRI
Field	center	NE	center
Exposure (s)	36,060	31,785	27,328
Effective energy band (keV)	0.35–2.9	0.30–2.4	0.5–4.5
Threshold luminosity[a] (ergs s^{-1})	4.4×10^{36}	4.4×10^{36}	9.1×10^{36}

[a] 0.5–4.5 keV, near field center; this is spectrum and position dependent.

1.1×10^{21} cm^{-2}. Most spectral fits were consistent with this value, thus indicating little intrinsic source absorption. The HRI does not have spectral resolution, but its counting rate is relatively insensitive to typical spectral parameters other than the absorption. All absolute luminosity statements based upon either IPC or HRI in this *Letter* are uncertain by $\pm 50\%$ because of the above difficulties.

Relative fluxes can be determined more accurately. Seven of the 10 sources detected by both the HRI and IPC are too weak or exhibit variability and are not suited for verifying the calibration of the HRI relative to the IPC. The remaining three sources are consistent within the stated uncertainties. The effects of variability can be reduced by averaging many sources. The sum of the luminosities of HRI sources within 5′ of the nucleus is 1.31×10^{39} ergs s^{-1}, whereas the IPC estimate of this region is 1.17×10^{39} ergs s^{-1}, or about 11% less. This indicates reasonable consistency between the two data sets and also argues against a large contribution by many sources which happen to be slightly below our threshold. The total luminosity of all detected sources is 2.3×10^{39} ergs s^{-1}; if we obtain the same flux from the unanalyzed southwest field as from the northeast, then the total luminosity due to detected sources in the 0.5–4.5 keV band will be about 2.7×10^{39} ergs s^{-1}, which can be compared to the *Uhuru* M31 estimate of 2.3×10^{39} ergs s^{-1} in the 2–6 keV band. We believe that most of the X-ray emission from M31 comes from the strong sources we are observing.

III. INDIVIDUAL SOURCE CHARACTERISTICS

The most interesting single object is source 14, which nominally is 2″.1 from the nucleus of M31. Globular clusters, to be discussed later, provide a measure of our location accuracies and indicate that 5″ is a conservative coincidence requirement.

The X-ray source density near the nucleus is such that the probability of an ordinary X-ray source being located less than 5″ from the nucleus by chance is about 0.1. The association with the nucleus also is supported by the lack of detected variability in this source, such as is typical of bright X-ray sources in our Galaxy and which we also have found for the luminous sources in M31. Assuming that this 9.6×10^{37} ergs s^{-1} source is the nucleus, we discern a marked contrast with the center of our own Galaxy. The X-ray luminosity of the nucleus of M31 would be approximately 10^3 times that of any steady point source within 0°.5 of our own galactic nucleus (Epstein *et al.* 1979), although comparable to strong transient sources which have been observed near the galactic center, and still much weaker than the emission from the nuclei of active galaxies. The M31 nucleus emission at 1415 MHz is only about 0.06 that of Sgr A (van der Kruit 1972). This suggests a thermal source of the M31 X-ray radiation—possibly accretion of gas clouds onto a massive object, as has been suggested to be present near the center of our own Galaxy (see, e.g., Rodriguez and Chaisson 1979). Future *Einstein* observations of M31 will allow us to determine if the nuclear emission varies on a time scale of months, which would not be expected for such models.

The region northeast of the nucleus (near source 14) is particularly complex. There are three obvious point sources in this region which account for most of the emission. We interpret the data to indicate that much of the remaining flux from this region is the result of two additional point sources, but we cannot exclude the possibility that this is diffuse emission similar to that seen near the center of our Galaxy. Our interpretation is supported by marginal evidence for periodicity in one of these sources, the probability being ~0.055 of a nonvarying source giving the observed Fourier amplitude.

We have searched for position coincidences between the X-ray sources and two lists of supernovae remnants kindly provided to us prior to publication by Kirshner (1979) and by D'Odorico, Dopita, and Benvenuti (1979). These combined lists include 13 remnants in our fields of view; one clear coincidence was found—a supernova remnant associated with the Baade and Arp (1964) region 521 was observed with both HRI and IPC. The X-ray luminosity is about 2.2×10^{37} ergs s^{-1}. We do not detect emission at the position of S. Andromedae 1885.

IV. GROUP PROPERTIES

It is useful to divide the X-ray sources into three groups—inner bulge, Population I, and globular clusters—although further subclassifications eventually will be necessary. We have compared the HRI source positions with the globular cluster list of Sargent *et al.* (1977), and find five coincidences. Four of these five are in the inner part of the HRI field, where our position errors are less; these have an average separation of 3″.5, the worst being 4.9. The globular cluster numbers from the list of Sargent *et al.* (1977) thus identified as X-ray sources are 148, 198, 199, 200, and 213. There also are eight IPC sources within 1′ of listed globular clusters for which no HRI positions are available; approximately four would be expected by chance. We find five X-ray sources among the 60 globular clusters Sargent *et al.* (1977) list in the HRI field, and estimate approximately nine X-ray sources in the 237 globular clusters listed in our total observed fields. This is similar to the results obtained in our Galaxy, where seven of 150 clusters searched have such luminosities (Grindlay 1979). Two

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additional HRI sources which are coincident with bright objects have been observed optically, and a very preliminary inspection of these spectra suggests that these sources also are globular clusters.

The source positions and detector fields are plotted on an optical photograph of M31 in Figure 3 (Plate L13). The association of the outer X-ray sources with spiral features is quite apparent, although certain regions, such as the northeast, seem relatively overpopulated. The X-ray source positions are plotted on the H I map of Emerson (1976) in Figure 4. The sources possibly associated with globular clusters are indicated; the correlation of the remaining X-ray sources with the neutral hydrogen is striking. This, however, should not be surprising because we expect X-ray sources to be associated with young massive stars, and in M31 the indicators of Population I activity such as OB associations, H I, H II, CO, and dust are concentrated in a ring (see Fig. 4) centered at about 9 kpc from the nucleus (Emerson 1974, 1976, and 1978; Baade and Arp 1964; Berkhuijsen 1977; Combes *et al.* 1977*a*, *b*).

The X-ray positions in the inner part of M31 are

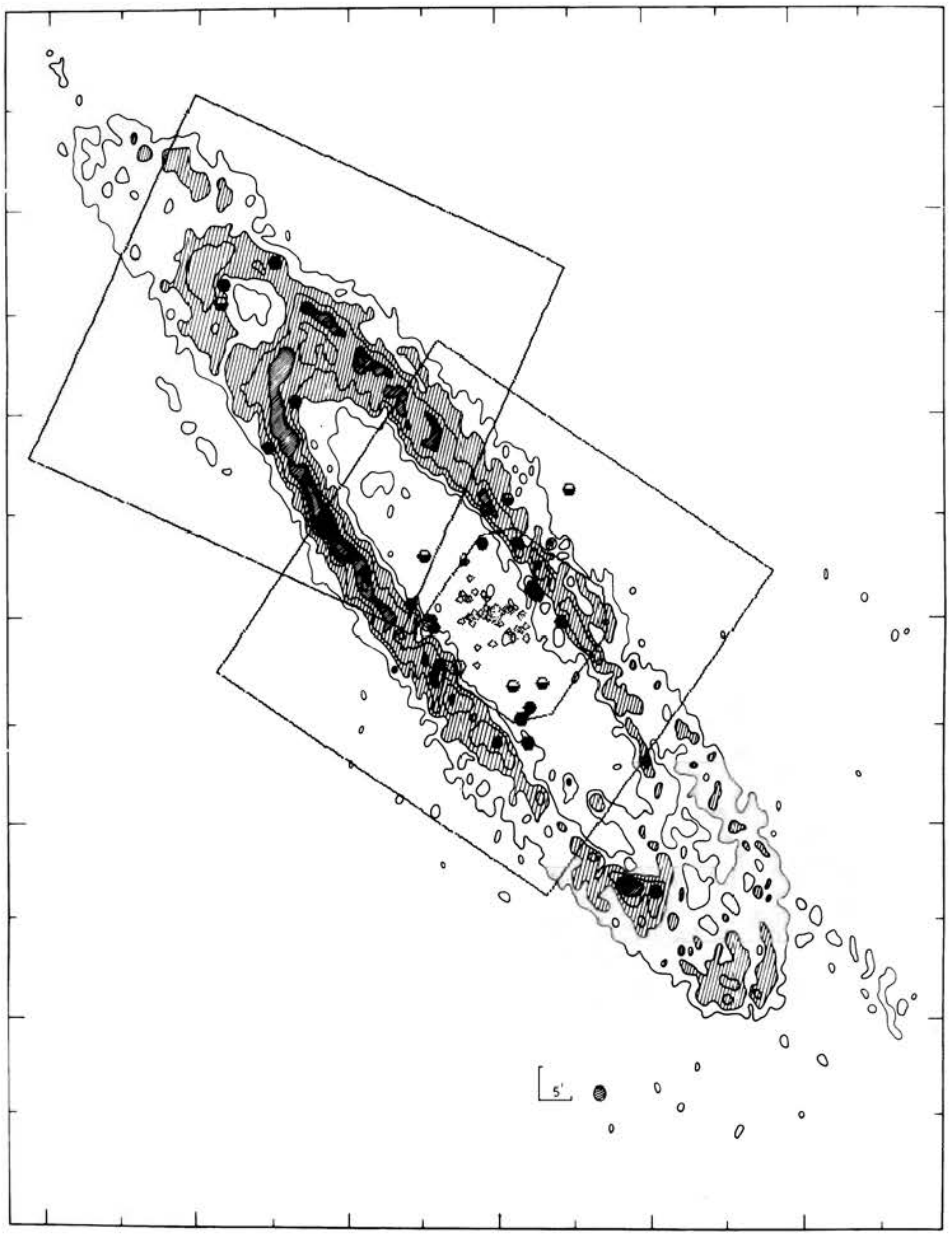


FIG. 4.—X-ray source positions superposed on the H I map of Emerson (1976). The larger symbols are IPC detections. Filled IPC symbols probably are Population I objects. Half-filled symbols are IPC sources located near globular clusters, but with position errors such that about one-half are expected to be spurious associations. The open IPC symbol is identified with a globular cluster through HRI observations. The correlation between H I emission and Population I X-ray sources is apparent.

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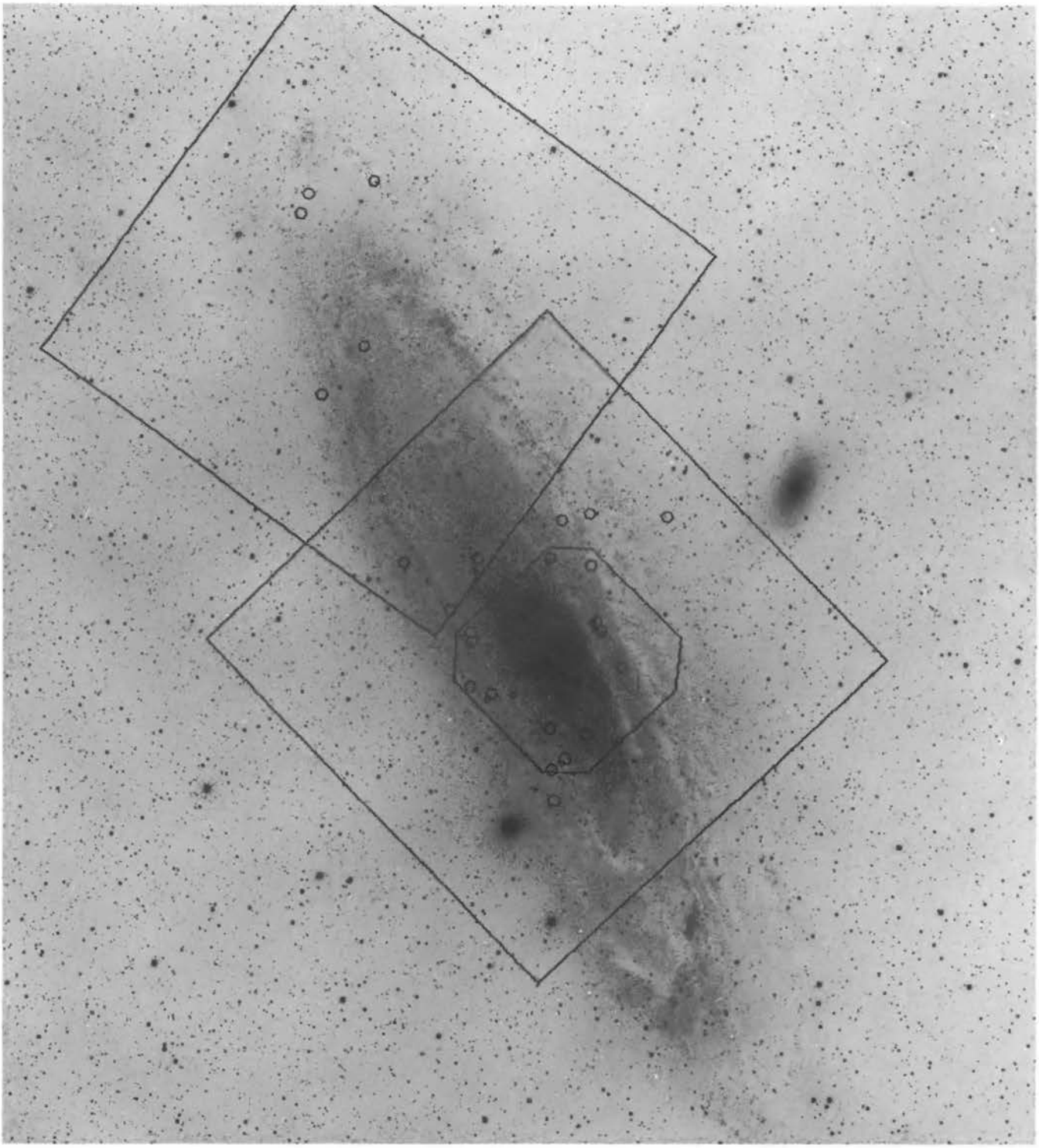


FIG. 3.—X-ray source positions superposed on an optical photograph of M31. The larger symbols are IPC detections with typical position errors of 1′. The smaller symbols are HRI detections; most of these are contained in the overexposed central region. The outer sources are associated with spiral-arm features or globular clusters. The detector fields are indicated.

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superposed on a Hale Observatory photograph in Figure 5 (Plate L14). The X-ray sources include a group concentrated around the nucleus and outlying sources which tend to be associated with inner spiral-arm features. We have divided these sources into Population I and inner bulge, placing a source into Population I if any dust or spiral-arm features are observed at the source position. This separation results in 18 inner bulge point sources including the nucleus candidate plus three diffuse or confused regions located within 2′ of the nucleus, or 400 pc, assuming a spherical distribution so that projection effects can be ignored.

The average M31 inner bulge source luminosity is 4.5×10^{37} ergs s^{-1}, whereas the average Population I source luminosity is 2.8×10^{37}; both of these results are biased toward higher values by our threshold of approximately 9×10^{36} ergs s^{-1}, but, as discussed previously, there is evidence that most of the X-ray luminosity is provided by the observed sources in the nuclear regions, and so a lower threshold, if anything, would tend to increase the separation of the two source groups. The observed difference is not a result of a lower threshold in the IPC which contributes only to Population I sources; the average luminosity of the 29 HRI Population I point sources is 2.1×10^{37} ergs s^{-1}. The optical bulge of M31 is larger than our effective radius of 400 pc; Morton, Andereck, and Bernard (1977), for example, quote 1000 pc. There are 16 sources we call Population I inside of 1000 pc; this is higher than the typical density of sources in the disk, but the average luminosity of this group is 2.2×10^{37} ergs s^{-1}, which is slightly less than the average Population I luminosity found outside the optical bulge and therefore supports our present assignment of these to Population I.

The luminosity distributions for these groups of sources and the total source set are plotted in Figure 6. We have binned the luminosities to facilitate comparisons with the distributions found by Clark *et al.* (1978) for the luminosities of sources in our galaxy and the Magellanic Clouds. The M31 results are quoted for the 0.5–4.5 keV band, whereas Clark *et al.* (1978) chose the 2–11 keV interval, and so some care must be taken in comparing the data sets. The absolute values of the bulge source luminosities observed in our Galaxy and M31 are quite similar; Clark *et al.* (1978) find six bulge sources in our Galaxy between our M31 threshold and 3.2×10^{37}, and 10 between 3.2×10^{37} and 3.2×10^{38}. We find 11 point sources in the lower interval and seven in the upper interval. The spatial distribution of these sources, however, is very different. The sources we consider to be inner bulge objects in M31 are contained in a 400 pc radius, which would correspond to 2°.3 at the position of our galactic nucleus, whereas the sources considered bulge objects in our Galaxy span 40° in longitude. There are only three sources listed in the fourth *Uhuru* catalog (Forman *et al.* 1978) within 2°.3 of the nucleus, and one of these is transient, compared to 18 point sources and three diffuse or confused sources in this region of M31. The difference is unlikely to be due to the bulge sources in

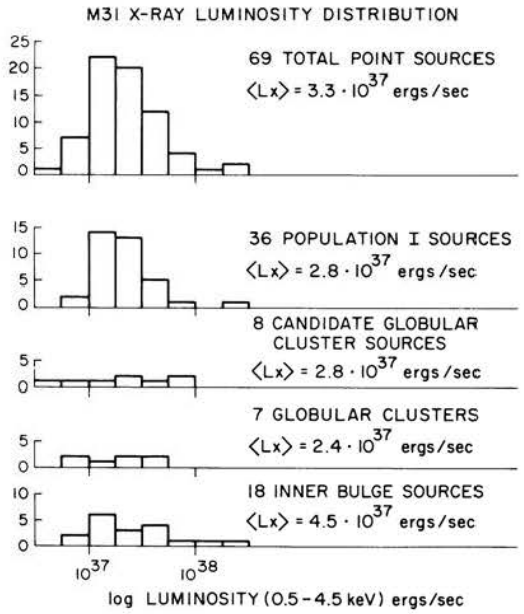


FIG. 6.—X-ray luminosity (0.5-4.5 keV) distributions for various categories of X-ray sources in M31.

M31 being so soft that they would not be detectable near our own galactic center; the best-fit temperature to the aggregate emission from this region detected with the *Einstein* IPC is 5 keV, which is high enough so that the ~3 keV absorption cutoff to our own galactic center would not have precluded observation of such sources in our Galaxy. We therefore conclude that the X-ray source density near the center of M31 is far greater than that of our own Galaxy. Clark *et al.* (1978) find 26 sources in our Galaxy with luminosities above their completeness threshold of about 5×10^{36} ergs s^{-1}; we find 76 in M31 and can expect about 80 when the southwest field is added, or a factor of 3.1. This is only slightly higher than the mass ratio of 2.4 found by van den Bergh (1975). Our ratio of the number of sources called bulge and Population I is about (1:2), which is quite different from the ratio (2.7:1) found by Clark *et al.* (1978), and there is a question of whether this results from the different criteria used or a difference between the two galaxies. Markert *et al.* (1977) and Jones (1977) argue that the bulge sources in our Galaxy can be distinguished from the disk population by softer spectra as well as higher luminosities. Our division is based upon morphology, but we also find higher luminosity sources in our inner bulge group. Clearly, some sources could be misclassified in either survey, but it is likely that the ratio of bulge to disk X-ray sources is lower in M31 than in the Galaxy.

The 400 pc radius defining the X-ray inner bulge group is near that where Rubin, Ford, and Kumar (1973) find a local minimum in the emission-line velocities (see, however, Peterson 1978). Rubin and Ford (1971) also find that the gas motions within this region show a complex velocity field superposed on the rapid rotation, with evidence for expansion at velocities up to

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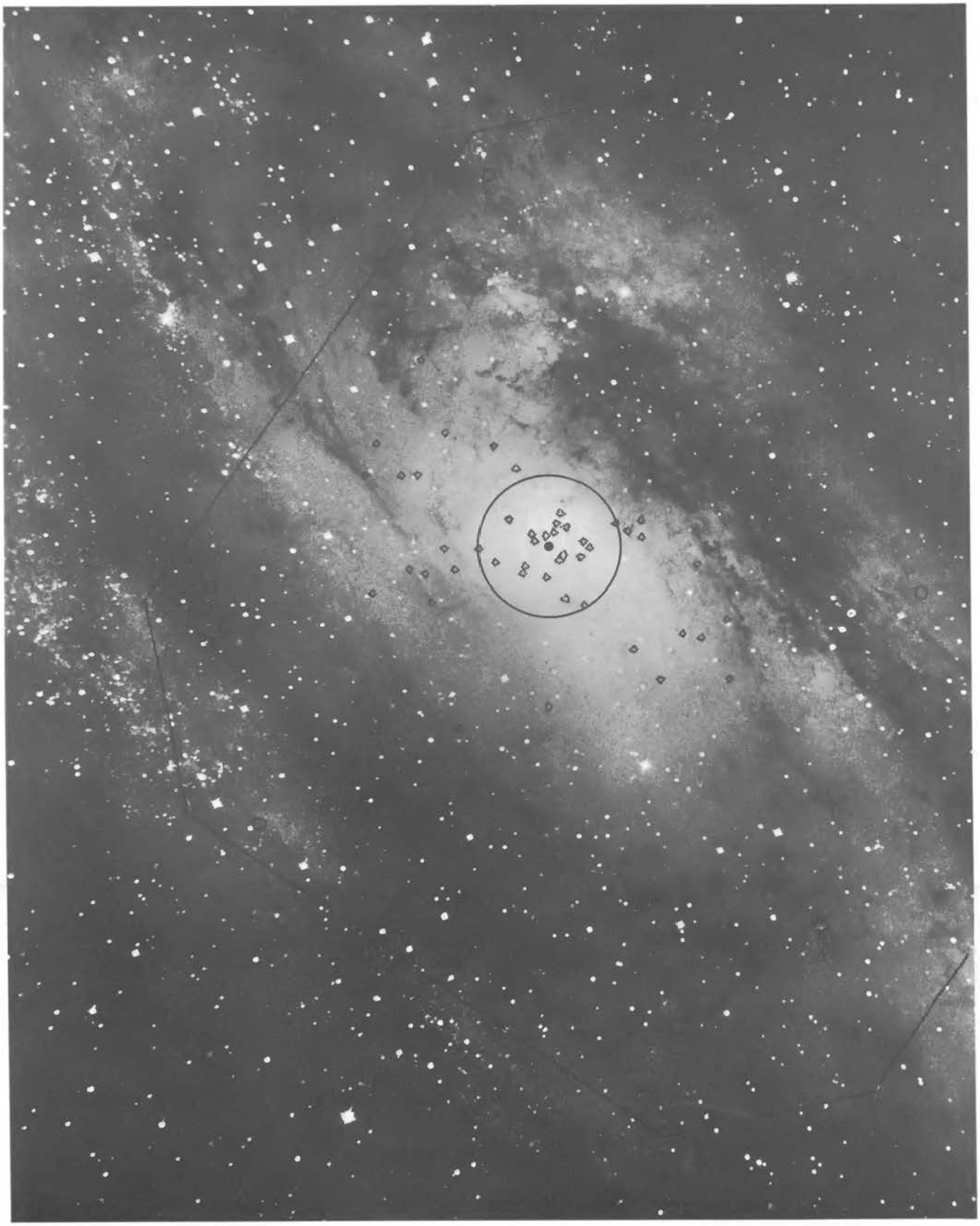


FIG. 5.—X-ray source positions superposed on a Hale Observatory photograph of the central region of M31. The dense group of sources categorized as inner bulge are located within 2′ of the nucleus; the detector field opposite boundaries are approximately 25′ apart and can be used as a scale.

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100 km s^{-1}. This ~400 pc radius region thus may constitute a distinct structure within M31. Rubin and Ford (1970) estimate that only 0.015 of the mass of M31 is contained within 400 pc, and most of that is low-mass, late type stars, and yet we find that this region is responsible for one-third of the X-ray emission from M31.

Ten of the 29 HRI Population I sources are associated with bright visible objects. The actual number of such systems must be considerably higher because much of this region is obscured optically. We plan to observe many of these objects optically during the coming months. There also appears to be an association of X-ray sources with dust-lane boundaries; we have not established if this is statistically significant; if we are able to establish this, then it will be reasonable to conclude that these objects are much closer to their places of origin than expected from typical models of their evolution (e.g., van den Heuvel 1978).

V. SUMMARY

We have observed 69 X-ray sources in M31 which appear pointlike at our resolution, and seven additional diffuse or confused regions. We find that the sources can be divided into inner bulge, globular cluster, and Population I objects; these contribute about 0.33, 0.11, and 0.56 of the X-ray flux, respectively. The inner bulge sources in M31 are more luminous than the Population I or globular cluster sources. The Population I sources are associated with bright visible objects, dust, neutral hydrogen, and other Population I tracers. The number and luminosity of the inner bulge X-ray sources in M31 are similar to those observed in the bulge of our own Galaxy, but the spatial extent is much less, those in M31 being contained within 400 pc of the nucleus. The nucleus of M31 is likely to be a 10^{38} ergs s^{-1} X-ray source, which is not unusual, but still a factor of 10^3 brighter than the nucleus of our own Galaxy.

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