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THE X-RAY SPECTRAL PROPERTIES OF THE BULGE OF M31

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ABSTRACT

We report the results of a spectral analysis of the *Einstein* observations of the bulge of M31. The data can be fitted with a hard thermal spectrum with characteristic temperature $kT \approx 6$–13 keV (at 90% confidence). No intrinsic absorption above the galactic value of N_H is required. These results are in agreement with the presence in the bulge of M31 of a population of low-mass binary sources similar to those of the Milky Way.

Subject headings: galaxies: individual (M31) — X-rays: binaries — X-rays: spectra

I. INTRODUCTION

The purpose of this paper is to report the results of a study of the bulge of the nearby galaxy M31, using the spectral information of the *Einstein* satellite Imaging Proportional Counter (IPC) and of the *Einstein* Monitor Proportional Counter (MPC, for a description of the *Einstein* observatory see Giacconi *et al.* 1979). The scope of this project is twofold. We seek direct information on the soft (0.2–4.0 keV) energy spectrum of galactic bulge sources, that cannot be obtained by the study of sources in the Milky Way, because of the line of sight interstellar absorption. We also seek spectral information that could be used to help us constrain the nature of the X-ray emission of more distant galaxies.

Most of the information available on the X-ray spectra of galactic bulge sources comes from the observations of the Milky Way with nonimaging X-ray satellites, which were typically sensitive only at energies above 2 keV. These spectra were found to have characteristic temperatures $kT \approx 5$–10 keV and low-energy cutoffs consistent with the line-of-sight absorption, which can be as high as 2–3 keV in the direction of the Galactic center (e.g., Mason *et al.* 1976; Jones 1977; Markert *et al.* 1977). Because of these cutoffs, there is no direct knowledge of the spectral behavior of these bright sources below 2 keV. The *Einstein* observations of M31 provide a unique opportunity for studying the spectral properties of bulge sources in this up to now unexplored energy range, because only a low line-of-sight galactic absorption affects the X-ray emission of the bulge of M31. This amounts to $N_H \approx 10^{20}$ cm^{-2} (Stark *et al.* 1987), which corresponds to a low-energy cutoff of ~0.4 keV.

The determination of the spectral properties of the bulge of M31 can also be used for confirming some of the inferences from the spectral analysis of more distant spiral galaxies (Fabbiano and Trinchieri 1987) and eventually for constraining the origin of the X-ray emission of the less X-ray bright elliptical galaxies. This last question, in particular, is at the moment a matter of controversy. Some authors (Trinchieri and Fabbiano 1985; Canizares, Fabbiano, and Trinchieri 1987) have suggested that the X-ray luminosity of low-luminosity ellipticals is dominated by a collection of galactic sources, similar to those in the bulge of M31. Others (Forman, Jones, and Tucker 1985) instead suggest that the X-ray luminosity of essentially *all* elliptical galaxies (excluding only very low luminosity galaxies with $M_B \geq -19$) is dominated by a hot gaseous component, with typical $kT \approx 1$ keV, similar to the one detected in the more luminous ellipticals. If the spectral properties of the bulge of M31 differ from those of luminous elliptical galaxies, they might be used as a future benchmark to test this open question, by comparing them to those of low-luminosity elliptical galaxies, which will be measurable with future X-ray experiments.

The bulge of M31 is resolved into several bright point sources with the high-resolution *Einstein* HRI, although it appears only as a bright, extended source with an integrated luminosity $L_x \approx 10^{39}$ ergs s^{-1} in the IPC (Van Speybroeck *et al.* 1979; Van Speybroeck and Bechtold 1980). We report here the results of a spectral study of this extended IPC source. We also analyse the data of the *Einstein* MPC.

II. SPECTRAL ANALYSIS AND RESULTS

a) IPC Analysis

To study the spectral properties of the bulge of M31 we have used a long IPC observation centered on the nuclear region (*Einstein* sequence I574), obtained 1979 January 11. The analysis of these data was not completely straightforward. We had to face two nonstandard conditions: first, the field is rather complex and rich in partially unresolved sources (see Fig. 1 of Van Speybroeck *et al.* 1979), and it therefore requires both care and value judgment to extract the background-subtracted data for the spectral analysis; second, the instrumental gain was increasing constantly during the observation, resulting in a shift of the energy boundaries of the spectral channels.

To derive the background-subtracted data we have taken the following approach: we have extracted the "source" counts from a circle of 5′ radius (1 kpc at the distance of M31, corresponding to the optical size of the bulge; Morton, Andereck, and Bernard 1977) centered on the X-ray centroid position at R.A. = $0^h39^m57^s$ and decl. = 40°59′46″, and we have extracted the background counts from a surrounding annulus of 7′.5 and 10′ inner and outer radii from which the area occupied by bright sources had been excluded. The "source" and "background" areas are shown in Figure 1. Using this approach we subtract from the source counts a fairly close approximation of the "true" field background. Taking the background from closer in, we would have included in it a significant amount of unresolved emission from the inner arm sources. These sources are shown clearly by the high-resolution HRI image of the central region of M31 (Van Speybroeck *et al.* 1979). We have checked our procedure by

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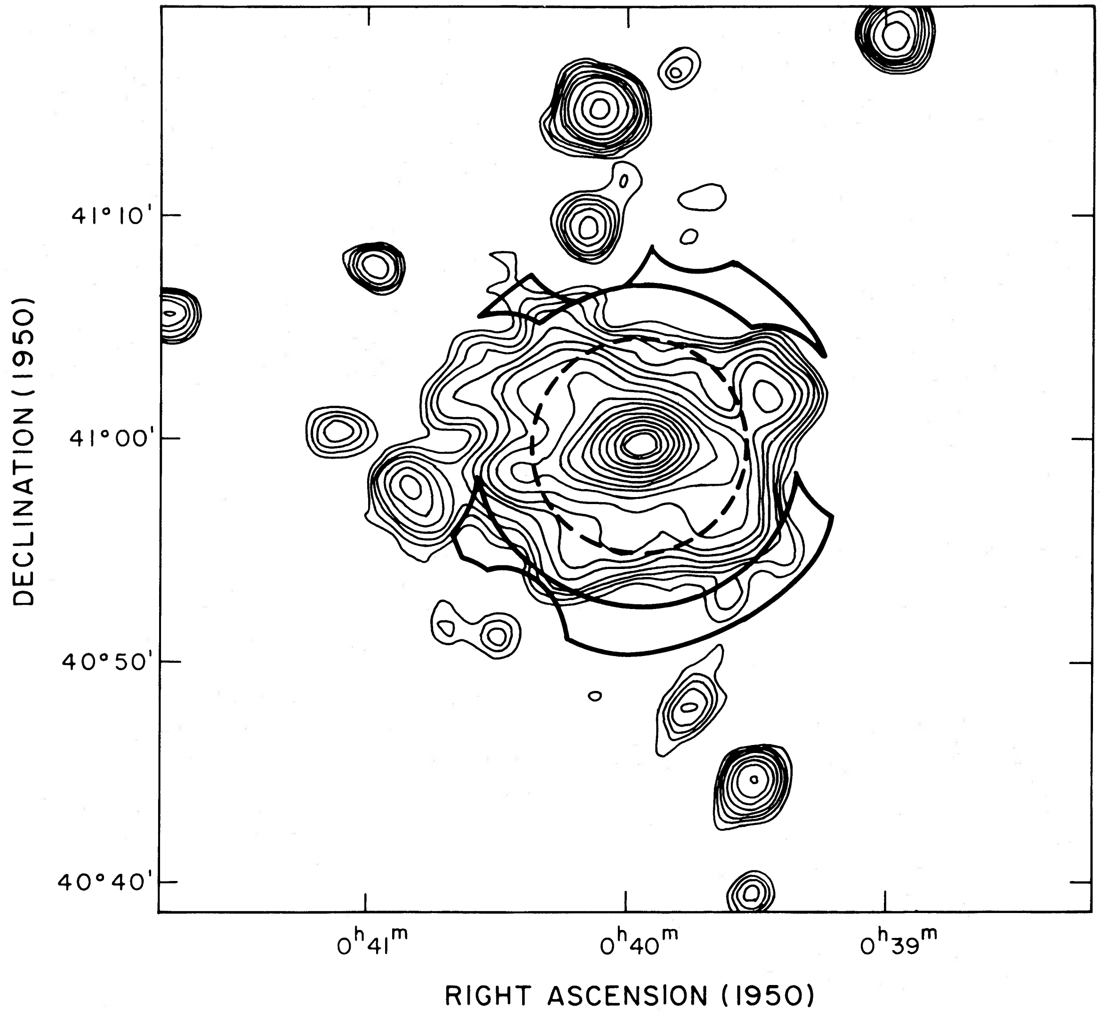

FIG. 1.—Contour plot of segment 2 of the IPC observation of the bulge of M31 (see text). The first contour is at the 2 σ level above the background. The dashed circle has a radius of 5′ and encloses the area used for the spectral analysis. The background was estimated from the area within the solid lines between 7′.5 and 10′ radii.

examining a radial profile of the bulge region, from which identifiable point sources outside the 7′.5 circle had been subtracted, and comparing it to a radial profile of the field background template produced by the on-line software (Harnden *et al.* 1984). Outside of the inner 7′.5 circle, the two radial profiles agree closely.

We have also analyzed data from the entire central IPC region within a circle of 7′.5 radius and with the same background subtraction as above, and from the inner bulge region within a 3′ circle, which includes the innermost enhanced emission region, and with the background estimated from the surrounding annulus of 3′ and 5′ inner and outer radii. This latter approach is justifiable if the bulge sources are distributed with approximately spherical geometry, as might be suggested by the data (Long and Van Speybroeck 1983). The results of the analysis in these two cases are entirely consistent, within statistics, with those obtained from the 5′ source circle, and therefore will not report them in detail. However, this gives us confidence that uncertainties in the background subtraction cannot affect dramatically our results.

To ensure that the results of our analysis were not biased by the change in instrumental gain, we have divided the IPC data into five temporal segments, during which the gain remains relatively constant and we have analyzed them separately. In Table 1 we list the duration of each data segment, the instrumental gain, and the background subtracted source data with their statistical errors. To the data we have fitted thermal bremsstrahlung spectra with characteristic temperatures kT ranging from 0.1 to 15 keV and an equivalent hydrogen

TABLE 1

IPC DATA USED IN THE SPECTRAL ANALYSIS

Segment Number	Exposure Time (s)	Time-averaged Instrumental Gain (BAL)[b]	Net Counts ± Error
1	2253.4	18.7	1460 ± 46
2	9320.5	19.4	5260 ± 95
3	8301.9	20.5	4463 ± 87
4	7252.7	21.4	3743 ± 77
5	7439.7	22.3	3766 ± 84

[a] *Einstein* sequence I574, 1979 Jan 11.

[b] Peak channel (in the range 0–31) of the pulse-height distribution of an on-board aluminum calibration source.

columns N_H ranging from 3×10^{20} to 3×10^{21} cm^{-2}. We have excluded from the fit the lowest and the two highest spectral channels. The lowest channel was excluded because the instrumental gain during the observation gives unrealistically low energy boundaries. The two highest channels were excluded because there are substantial uncertainties in their calibration. A 3% error was added in quadrature to the statistical errors to take into account systematic uncertainties in the IPC calibration (D. Fabricant 1986, private communication).

To take into account spatial variations of the gain in the IPC field, we have used a procedure developed for the spectral analysis of extended sources (Fabricant and Gorenstein 1983). Although the M31 bulge source is not intrinsically extended, ~18 sources of similar intensity are present in the HRI image of the inner bulge (Van Speybroeck *et al.* 1979), and therefore the resulting effect in the IPC should be similar to that of a truly extended source. Nevertheless, to evaluate conservatively the effect of spatial gain variations, we have calculated the average effective gain for displacements of 1′ in various directions from the center of our "source" area and we have performed spectral fits for these different values of gain. We find that although the lower boundary on kT may vary somewhat, the confidence region in N_H is essentially unchanged, so that our conclusions (see below) remain unchanged.

The spectral fits to the five data segments consistently show a hard spectrum, with very little absorption at the low energies. The confidence region for the spectral parameters obtained with the data from segment 1 is not well constrained, reflecting the poorer statistics due to the shorter exposure time (see Table 1). Segment 2 (shown in Fig. 2) is the longest data segment and gives best-fit values of $kT = 13.5$ keV and $N_H = 5.1 \times 10^{20}$ cm^{-2}, with a minimum $\chi^2 = 3.5$ for 10 degrees of freedom. At the 90% confidence level $kT \geq 5$ keV and $N_H \approx (4.3\text{–}8.7) \times 10^{20}$ cm^{-2}. The other three data segments suggest even higher values of kT. However, the instrumental gain during these observations reaches extreme values, well beyond the calibrated region (D. Fabricant 1986, private communication). Therefore, although the spectrum of the bulge of M31 is undoubtedly hard, the exact values of kT to attach to this statement are uncertain. Also one should remember that the response function of the *Einstein* mirror does not reach beyond ~4.5 keV, and therefore the IPC is not optimal for measuring $kT \gtrsim 5$ keV.

The IPC is, however, ideal for measuring the low-energy spectral absorption. In Figure 2 we also have indicated the average N_H in the direction of the bulge of M31 (from Stark *et al.* 1987), with its 90% confidence limits (see Elvis *et al.* 1986 for the uncertainty on N_H measurements). This value could exceed somewhat the N_H in the central 5′ of M31, since the beam of

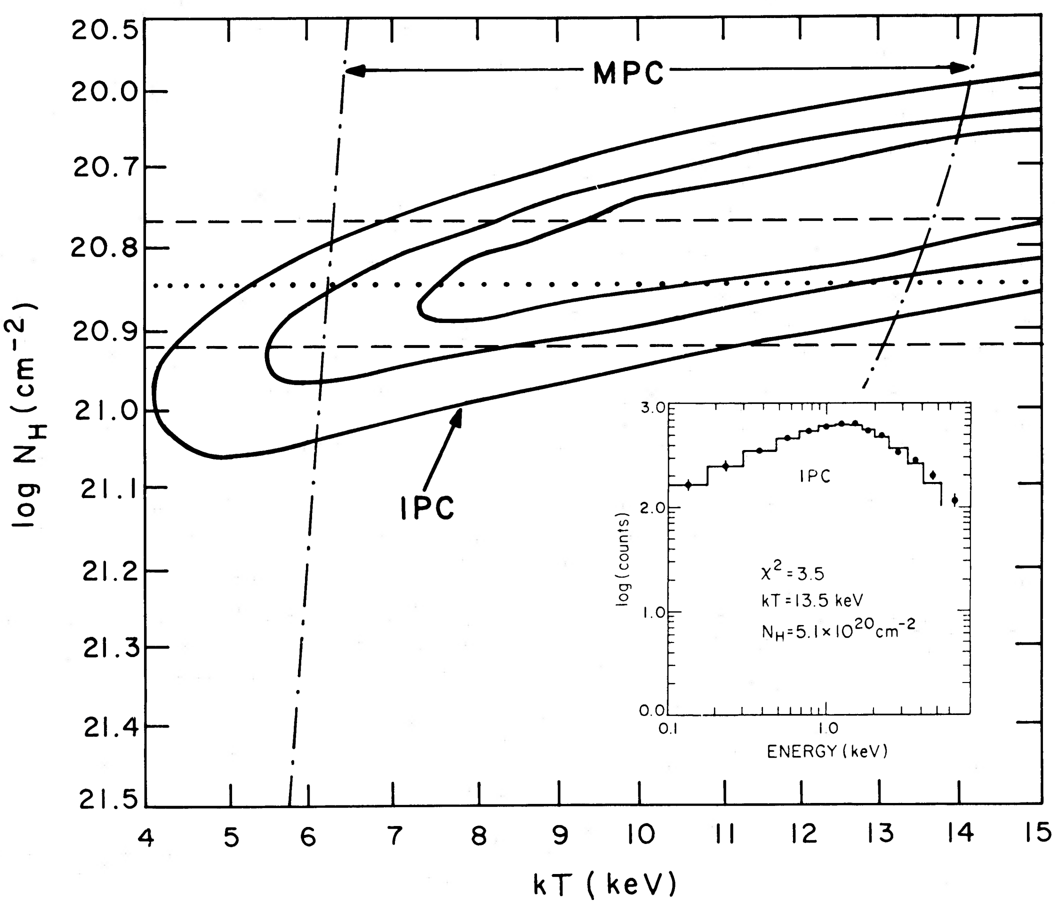

FIG. 2.—Confidence contours at 99%, 90%, and 68% (from outside in) for the spectral fitting of segment 2 of the IPC data to a thermal bremsstrahlung spectrum with low-energy absorption (see text for uncertainties of the IPC fit). The horizontal dotted line indicates the line of sight extinction (N_H), and the two dashed lines, its 90% confidence values (see text). The IPC data and the best-fit spectrum are shown in the insert. The dot-dashed lines represent the 90% MPC confidence contour.

the Stark *et al.* survey is $\sim 2°$ and would include some of the contribution of the bright H I ring of M31. (Although Emerson [1977] shows high-resolution H I maps of the central region of M31, he does not give a conversion between antenna-dependent measured H I column density and N_H in cm^{-2}. We therefore used the N_H value derived from the survey of Stark *et al.*) It is evident from Figure 2 that the spectral fit to the data segment 2 does not require absorption in excess of the line-of-sight value. A similar result is obtained by the spectral fits of the other data segments.

b) MPC Analysis

To get an independent measure of the parameter kT, we used the data from the *Einstein* Monitor Proportional Counter (MPC). The MPC has a field of view similar to that of the IPC and is co-aligned with the *Einstein* telescope axis. It is sensitive at higher energies than the IPC (up to ~ 20 keV), and it is therefore ideal for measuring kT values in the range 5–15 keV. It is, however, much less sensitive than the IPC at the low energies, and as a consequence, it is not very effective at measuring N_H. Moreover, the MPC is not an imaging instrument; therefore, it averages together all sources within its field of view.

Given the complexity of the M31 field, the MPC results could be contaminated by sources not belonging to the bulge of M31, as used in the IPC analysis. However, we do not consider this a major concern for the following reasons. The MPC has a pyramidal response function, with maximum sensitivity at the center of the field, therefore giving less weight to peripheral sources. Also, by comparison of the background-subtracted IPC counts from the source circle of 5′ radius (used in the above IPC analysis) and one of 7.′5 radius, which includes most of the detected photons, we find that the 5′ circle accounts for 83% of the photons in the field. A comparison of the fluxes detected by the IPC within the 5′ circle and by the MPC also gives fairly consistent results.

The MPC detects the central region of M31 with high statistical significance at a count rate of 2.08 ± 0.04 counts s^{-1}. The fit of a thermal bremsstrahlung spectrum with absorption to the data from the first six MPC spectral channels (energy ≈ 1.2–10.2 keV) yield a surprising low minimum χ^2 of 0.1 (for 4 degrees of freedom) at $N_H = 10^{21}$ cm^{-2} and $kT = 8.3$ keV. The last two spectral channels are not used in MPC spectral fits because of the very poor background determination. We worried about this very small χ^2 value, which might indicate an overestimate of the errors on the data. This cannot be due to poor statistics, since the detection is highly significant in all the spectral channels used in the analysis. It might be due to an overestimate of the systematic error arising from the uncertainties on the background subtraction. However, even excluding the systematic errors, the χ^2 remains very low, with a minimum $\chi^2 = 0.3$. Since we could not find any anomalies with either the data or the instrument, we are left with what we take as a relatively unlikely (probability $< 0.2\%$) example of a very good fit.

We also did an independent check of these results by analyzing the MPC data of the HRI observation of the bulge of M31 (*Einstein* sequence H579, data obtained on 1979 January 13–14). The pointing direction of the satellite was the same during this observation and the IPC observation of the bulge. Also for sequence H579 the bremsstrahlung fit to the MPC data is good, with a minimum $\chi^2 = 1.9$ at $N_H = 10^{21}$ cm^{-2} and $kT = 10.4$ keV. The 90% confidence contour is consistent with that of sequence I574. The 90% MPC confidence region of sequence I574 is shown in Figure 2 together with the IPC confidence contours. The IPC, which is sensitive at the low energies, constrains N_H to be consistent with the line-of-sight absorption (see also above) while the MPC, being sensitive at the higher energies, is able to constrain kT to be between 6 and 13 keV. Similar temperatures can be derived from unpublished *HEAO 1* A-2 data (D. Worrall 1986, private communication).

III. DISCUSSION AND CONCLUSIONS

Earlier surveys of galactic X-ray sources in the (2–10 keV) energy range (e.g., Jones 1977; Markert *et al.* 1977; see review of van den Heuvel 1980) have suggested a broad characterization of these sources in two classes: X-ray pulsars in massive binary systems which exhibit harder X-ray spectra with typical $kT > 10$ keV and frequently large intrinsic absorption columns (e.g., Cen X-3, Schreier *et al.* 1976; 4U 0900−40, Becker *et al.* 1978; 4U 1223−62, Swank *et al.* 1976); and low-mass binary X-ray sources, or "bulge" sources, which instead tend to have softer X-ray spectra with $kT \approx 3$–10 keV and absorption columns consistent with line-of-sight extinction (e.g., Sco X-1 and similar sources; Mason *et al.* 1976). More recent work suggests a more complicated picture, with possible black hole sources exhibiting very soft spectral components (White and Marshall 1984) and with low-mass binary X-ray sources exhibiting two-component spectra and iron K-line emission (Mitsuda *et al.* 1984; Swank and Serlemitsos 1985; Makishima and Mitsuda 1985; White *et al.* 1986).

The *Einstein* IPC and MPC cannot resolve individual X-ray sources in the bulge of M31. Consequently we can study only the average properties of the bulge sources in this galaxy. Moreover these instruments have only moderate spectral resolution, which does not justify multicomponent fits to the data. The χ^2 obtained in our fits to thermal bremsstrahlung spectra are acceptable. As we have shown in the previous section, we find characteristic temperatures $kT \sim 6$–13 keV, and equivalent hydrogen absorption columns consistent with line-of-sight absorption. This suggests that the spectral properties of the bulge sources of M31 are not substantially different from those of sources in the Milky Way. In particular they are consistent with those of low-mass X-ray binary sources. Given the stellar composition of the bulge (e.g., Bohlin *et al.* 1985), the latter are likely to be the counterpart of the point sources shown by the HRI to be responsible for the X-ray emission of the bulge of M31 (Van Speybroeck *et al.* 1979).

The spectral properties of the bulge of M31 strengthen the hypothesis that the average properties of binary X-ray sources are similar in different spiral galaxies. This supports the inference of a predominant X-ray binary component in the X-ray emission of spiral galaxies, whose X-ray spectra can be fitted with average $kT > 2$ keV (Fabbiano and Trinchieri 1987).

These spectral properties are also different from those of X-ray luminous elliptical galaxies, which exhibit softer X-ray spectra (Forman, Jones, and Tucker 1985; Trinchieri, Fabbiano, and Canizares 1986). Our results therefore give us a benchmark against which to compare the spectral properties of low-luminosity elliptical galaxies, in order to determine if their X-ray emission is dominated by the integrated throughput of binary X-ray sources or by the softer thermal emission of a hot interstellar medium (see Trinchieri and Fabbiano 1985; Canizares, Fabbiano, and Trinchieri 1987). Optically in fact the stellar content of the bulge of M31 is indistinguishable from that of elliptical galaxies (e.g., see Faber 1983; Oke, Bertola, and Capaccioli 1981; Bohlin *et al.* 1985), and evolved close binary systems in these galaxies are likely to behave like the X-ray bulge sources in M31. With the present data, however, the spectral properties of the low-luminosity ellipticals cannot be determined (Canizares, Fabbiano and Trinchieri 1987). The answer to this question, therefore, will have to wait for future, more sensitive X-ray missions, such as AXAF.

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