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## UNTANGLING THE X-RAY EMISSION FROM THE Sa GALAXY NGC 1291 WITH *CHANDRA*

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### ABSTRACT

We present a *Chandra* ACIS-S observation of the nearby bulge-dominated Sa galaxy NGC 1291. The X-ray emission from the bulge resembles the X-ray emission from a subclass of elliptical and S0 galaxies with low X-ray-to-optical luminosity ratios. The X-ray emission is composed of a central pointlike nucleus,  $\sim 50$  point sources that are most likely low-mass X-ray binaries (LMXBs), and diffuse gas detectable out to a radius of  $120''$  (5.2 kpc). The diffuse gas has a global temperature of  $0.32_{-0.03}^{+0.04}$  keV and metallicity of  $0.06 \pm 0.02$  solar, and both quantities marginally decrease with increasing radius. The hot gas fills the hole in the H I distribution, and the softening of the spectrum of the X-ray gas with radius might indicate a thermal coupling of the hot and cold phases of the interstellar medium as previously suggested. The integrated X-ray luminosity of the LMXBs, once normalized by the optical luminosity, is a factor of 1.4 less than in the elliptical galaxy NGC 4697 or S0 galaxy NGC 1553. The difference in  $L_{X, \text{stellar}}/L_B$  between the galaxies appears to be because of a lack of very bright sources in NGC 1291. No sources above  $3 \times 10^{38}$  ergs s<sup>-1</sup> were found in NGC 1291 when  $\sim 7$  were expected from scaling from NGC 4697 and NGC 1553. The cumulative  $L_{X, \text{stellar}}/L_B$  value including only sources below  $1.0 \times 10^{38}$  ergs s<sup>-1</sup> is remarkably similar between NGC 1291 and NGC 4697, if a recent surface brightness fluctuation-determined distance is assumed for NGC 4697. If this is a common feature of the LMXB population in early-type systems, it might be used as a distance indicator. Finally, a bright, variable [ $(1.6\text{--}3.1) \times 10^{39}$  ergs s<sup>-1</sup>] source was detected at the optical center of the galaxy. Its spectrum shows excess soft emission superposed on a highly absorbed power-law component, similar to what has been found in several other low-luminosity active galactic nuclei. However, the soft component does not vary in intensity like the hard component, indicating that the soft component is not reprocessed hard component emission.

*Subject headings:* binaries: close — galaxies: ISM — X-rays: galaxies — X-rays: ISM — X-rays: stars

### 1. INTRODUCTION

From a stellar population point of view, the large bulges of Sa galaxies closely resemble elliptical galaxies. It is therefore natural to ask if this similarity extends into the X-ray regime. With the launch of *Chandra*, our view of the X-ray emission from elliptical galaxies has become considerably clearer. The nature of the X-ray emission from X-ray bright (high X-ray-to-optical luminosity ratio,  $L_X/L_B$ ) elliptical galaxies had been known since the days of the *Einstein Observatory* to be primarily from hot  $10^7$  K gas (e.g., Forman, Jones, & Tucker 1985; Trinchieri, Fabbiano, & Canizares 1986), with a small percentage of the flux from a harder component (presumably the integrated emission from a collection of low-mass X-ray binaries [LMXBs]; Matsumoto et al. 1997). However, only *Chandra's* 0.5'' spatial resolution was able to resolve the X-ray emission from X-ray faint (low  $L_X/L_B$ ) elliptical and S0 galaxies into its constituent parts. In the X-ray faint elliptical galaxy NGC 4697, *Chandra* found that a majority of the X-ray emission emanated from a collection of point sources, primarily LMXBs, with the remaining X-ray emission from a lower temperature diffuse interstellar medium (ISM; Sarazin, Irwin, & Bregman 2000, hereafter SIB00). In these galaxies, much of the hot ISM has apparently been removed, leaving behind the X-ray binaries as the primary X-ray emission mechanism.

Whether spiral bulges more closely resemble the gas-rich X-ray bright elliptical galaxies or the stellar-dominated X-ray faint galaxies remains undetermined. Previous work with *Einstein* indicated that the average X-ray temperature of Sa galaxies was intermediate between elliptical galaxies and later-type spiral galaxies (Kim, Fabbiano, & Trinchieri 1992). Further comparisons with *ROSAT* revealed that the bulges of the two optically brightest Sa galaxies (NGC 1291 and NGC 3623) and the bulge of M31 had similar  $L_X/L_B$  values and X-ray colors as X-ray faint elliptical galaxies (Irwin & Sarazin 1998a, 1998b). Recent *ROSAT* High Resolution Imager (HRI) observations of NGC 1291 found that the radial surface brightness distribution of the X-rays followed a de Vaucouleurs profile suggesting that stellar X-ray sources were responsible for the observed X-ray emission (Hogg et al. 2001), although *ROSAT* Position Sensitive Proportional Counter (PSPC) data indicated that X-ray spectrum softened with increasing radius, which would not be expected from a purely stellar component (Bregman, Hogg, & Roberts 1995). But whether the X-ray emission from spiral bulges is dominated by a stellar component can only be confirmed using the excellent spatial resolution of *Chandra*. Here we present a *Chandra* observation of the nearby Sa galaxy NGC 1291 to resolve the question of the X-ray emission in spiral galaxies with large bulges.

### 2. TARGET AND DATA REDUCTION

NGC 1291 is the optically brightest Sa galaxy in the Revised Shapley Ames Catalog with a corrected apparent magnitude of  $B_0 = 9.17$ . Detailed optical imaging by de

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Vaucouleurs (1975) revealed a central lens surrounded by a large outer ring from which two faint spiral arms emanate. Sometimes classified as a transitional SB(s)0/Sa galaxy, there are no other optically bright galaxies in velocity space near NGC 1291, although recently a large concentration of faint low surface brightness galaxies have been found around NGC 1291 (Kambas et al. 2000). The distance to NGC 1291 is uncertain, and literature values range from 6.9 to 13.8 Mpc. De Vaucouleurs (1975) gives a distance of 8.9 Mpc by assuming that the brightest stars in the weak spiral arms of NGC 1291 have an absolute magnitude of  $M_B = -9.5$ , and this is the distance we have assumed for this work. The corrected galactocentric velocity is  $674 \text{ km s}^{-1}$  (de Vaucouleurs 1975). At a distance of 8.9 Mpc,  $1'$  corresponds to 2.6 kpc.

In this paper, we will concentrate on X-ray sources and diffuse emission seen in projection within the optical bulge of NGC 1291. We will define the bulge to be the region within an ellipse centered on the optical nucleus, with major and minor axes of  $4'.5$  and  $3'.7$ , respectively, and at a position angle of  $170^\circ$  (de Vaucouleurs 1975).

NGC 1291 was observed with the Advanced CCD Imaging Spectrometer (ACIS) on board *Chandra* at two epochs, on 2000 June 27–28, and again on 2000 November 7. The

first observation (hereafter OB1) was awarded to us in AO-1 of *Chandra*, while the second observation (hereafter OB2) was graciously donated to the *Chandra* archive early by Andrea Prestwich. OB1 contained one small background flare, while over a third of OB2 was taken during times of high background. The total usable exposure for OB1 and OB2 was 37,409 s and 23,016 s, respectively. Both OB1 and OB2 were taken when the focal plane temperature was  $-120^\circ\text{C}$ . The observations were combined for the spatial analysis and treated separately for the spectral analysis. We present data only from the backside-illuminated S3 chip. Exposure maps were generated to correct the images for vignetting. An exposure map appropriate for an energy of 0.75 keV was generated for soft-energy images, while an exposure map appropriate for an energy of 3 keV was created for hard-energy images. The newest spectral responses available (acisD2000-01-29fef\_piN0002.fits) were used in the spectral analysis.

### 3. SPATIAL ANALYSIS

#### 3.1. X-Ray Images

The 0.3–6 keV *Chandra* image of the merged OB1+OB2 observation is shown in Figure 1. It was found that omitting

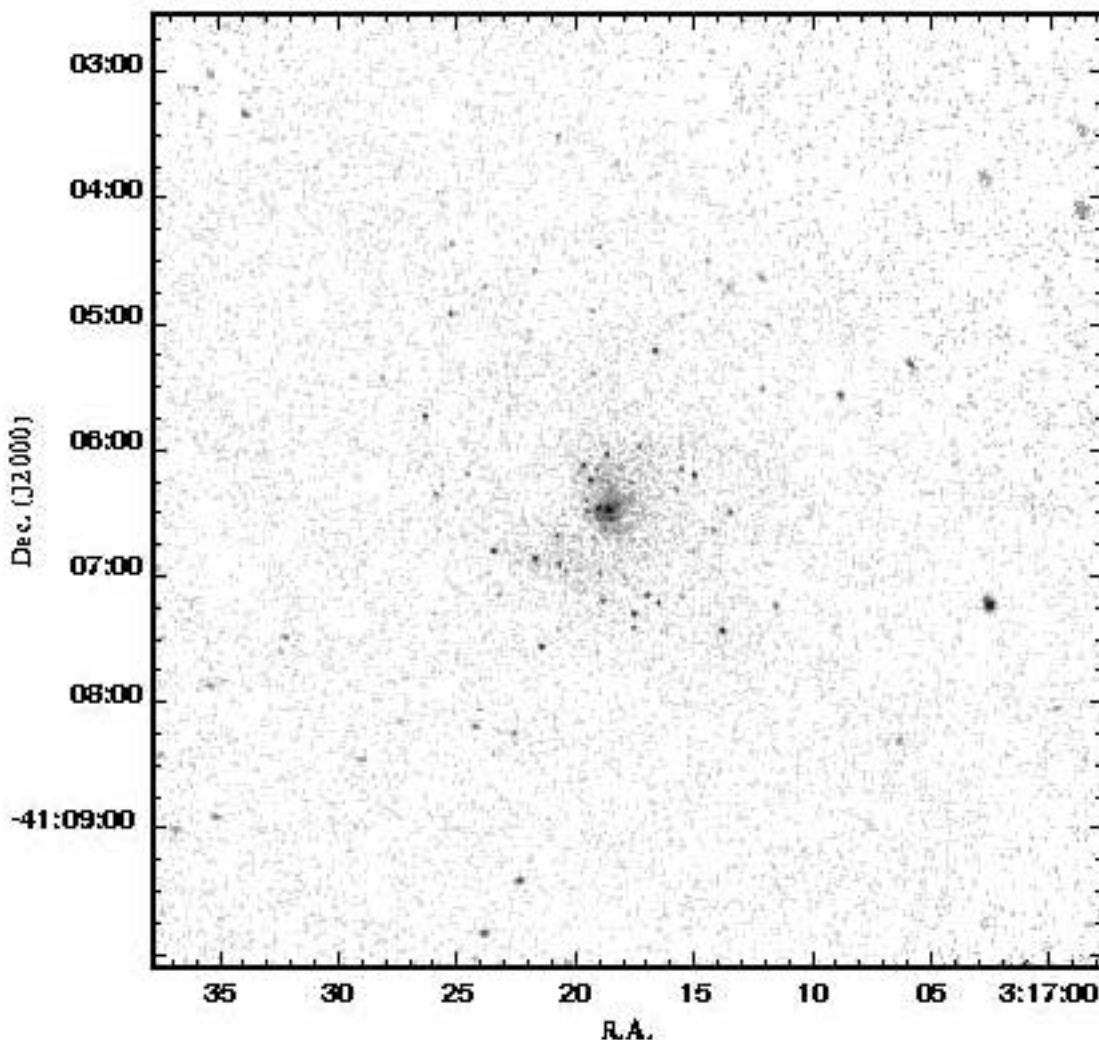


FIG. 1.— 0.3–6.0 keV image of the OB1+OB2 ACIS-S observation of NGC 1291. The image has been smoothed with a Gaussian of width  $0'.5$  to bring out point sources and diffuse emission.

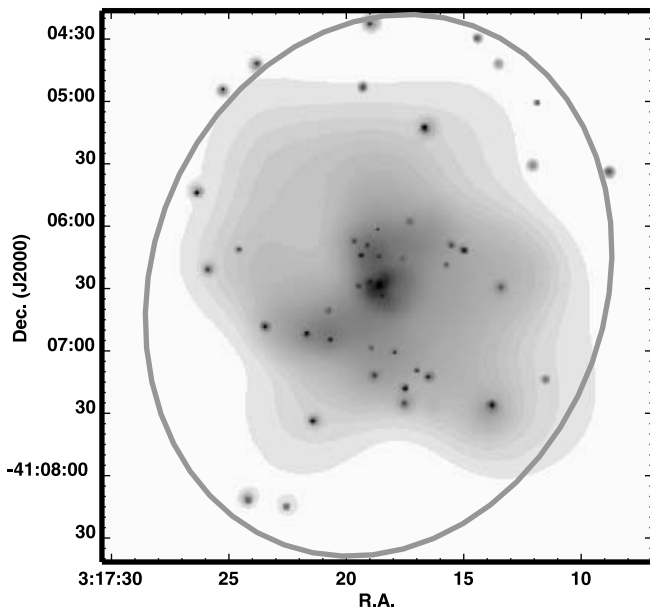


FIG. 2a

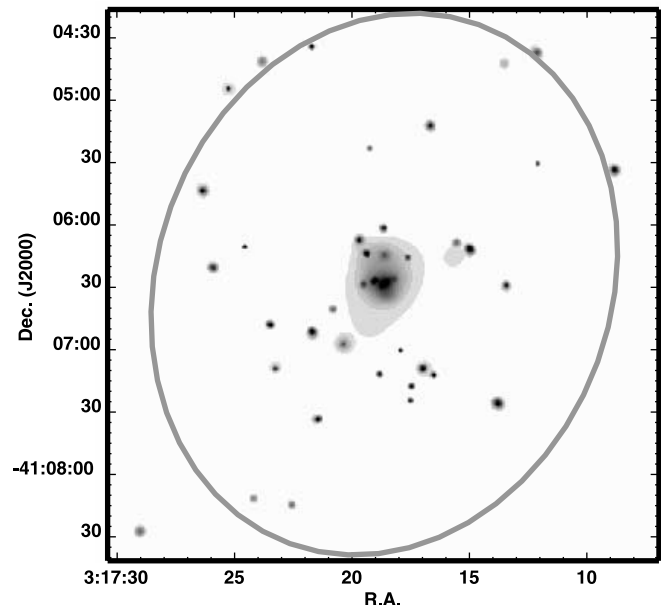


FIG. 2b

FIG. 2.—Inner  $4\frac{1}{2} \times 4\frac{1}{2}$  of NGC 1291 in the (a) 0.3–1.0 keV and (b) 1.5–6.0 keV energy band. The images have been adaptively smoothed to a minimum signal-to-noise ratio of 3 per smoothing beam. The ellipse represents the optical extent of the bulge as determined by de Vaucouleurs (1975).

energy channels above 6.0 keV reduced the background by 51% while decreasing the source emission by only 4%. The image has been lightly smoothed with a Gaussian with a width of 1 pixel to bring out the point sources. Adaptively smoothed images of the inner  $4\frac{1}{2} \times 4\frac{1}{2}$  for two energy bands (0.3–1.0 keV and 1.5–6.0 keV) are shown in Figure 2. The images illustrate the major X-ray-emitting components of the galaxy: a very bright central point source (most likely an active galactic nucleus [AGN]), many fainter point sources (most of which are LMXBs in NGC 1291), and centrally concentrated diffuse emission that is much more pronounced in the soft band. The diffuse emission is more or less circularly symmetric, although there are some asymmetries at intermediate radii. These asymmetries argue that the origin of most of the soft emission is hot gas rather than from a stellar component (which should be distributed like the optical light). It is unlikely that the majority of the asymmetric diffuse emission is from unresolved sources below the detection limit, since similar diffuse features are not seen in the 1.5–6.0 keV image. Nor is it likely that sources below the detection threshold of this observation have extremely soft spectra, since our preliminary work on sources in the bulge of M31 shows that there is no softening of LMXB spectra for sources with luminosities down to  $10^{36}$  ergs  $s^{-1}$ . The gas is contained almost entirely within the optical confines of the bulge, which is shown in Figure 2.

### 3.2. Point Sources

We used the CIAO program WAVDETECT to detect X-ray point sources in OB1 over the 0.3–6.0 keV energy range. A minimum detection threshold of  $3\sigma$  was adopted. This corresponded to a limiting 0.3–6.0 keV count flux of  $3.0 \times 10^{-4}$  counts  $s^{-1}$  and a limiting 0.3–10 keV luminosity of  $2.0 \times 10^{37}$  ergs  $s^{-1}$  at the assumed distance of 8.9 Mpc, assuming the spectra of all sources but the central source are described by a power law with  $\Gamma = 1.56$  (see § 4.1 below).

Here we concentrate on the sources seen in projection within the bulge of NGC 1291. A total of 48 sources were detected from the bulge region in OB1 and are listed in Table 1 in order of increasing distance from the center of NGC 1291. For the count-to-luminosity conversion, we assume 1 count  $s^{-1} = 6.80 \times 10^{40}$  ergs  $s^{-1}$  (0.3–10 keV band) except for the central source, where we assume a spectrum based on the spectral fit for that source (§ 4.3).

We constructed the luminosity function of the bulge X-ray sources. Since the luminosity of LMXBs in our own Galaxy can vary on timescales shorter than a few months, it is unclear whether merging the two observations will lead to an accurate assessment of the luminosity function of the sources in NGC 1291. Ideally, one wants the instantaneous distribution of the luminosities, so we analyze only those sources detected in the longer of the two observations, OB1 (although it should be noted that the luminosity function of OB1+OB2 was not substantially different from that of OB1 alone). The cumulative luminosity function for the 47 non-central sources detected in OB1 is shown in Figure 3. The central source was not included, as it is most likely an AGN. The luminosity function is roughly a power law between  $3 \times 10^{37}$  and  $2 \times 10^{38}$  ergs  $s^{-1}$ . There is a steep drop-off above  $\sim 2.5 \times 10^{38}$  ergs  $s^{-1}$ . The luminosity function also may flatten somewhat below  $\sim 3 \times 10^{37}$  ergs  $s^{-1}$ . However, it is possible that this is due to incompleteness near the detection threshold ( $2.0 \times 10^{37}$  ergs  $s^{-1}$ ), which might be due to the increase in the width of the instrumental point-spread function with distance from the center, or to reduced point-source sensitivity in regions of high diffuse surface brightness. Simulations suggest that incompleteness affects the luminosity function up to a luminosity of about 1.5 times the detection threshold (e.g., Blanton, Sarazin, & Irwin 2001). Thus, we will only fit the observed luminosity function for  $L_X \geq 3 \times 10^{37}$  ergs  $s^{-1}$ .

We used maximum likelihood techniques to fit the luminosity function, as described in SIB00 and Sarazin, Irwin, &

TABLE 1  
DISCRETE X-RAY SOURCES IN BULGE

Source Number (1)	Name (2)	R.A. (3)	Decl. (4)	$d$ (arcsec) (5)	Count Rate ( $\times 10^{-4} \text{ s}^{-1}$ ) (6)	S/N (7)	$L_X$ ([0.3–10] keV $\times 10^{37} \text{ ergs s}^{-1}$ ) (8)
1.....	CXOU J031718.6–410628	3 17 18.60	–41 06 28.3	0.00	255.25 $\pm$ 9.09	28.09	305.20
2.....	CXOU J031718.7–410630	3 17 18.79	–41 06 30.2	2.86	19.67 $\pm$ 2.52	7.80	13.39
3.....	CXOU J031718.9–410627	3 17 18.98	–41 06 27.0	4.52	25.50 $\pm$ 2.87	8.88	17.36
4.....	CXOU J031718.2–410626	3 17 18.22	–41 06 26.4	4.70	8.96 $\pm$ 1.70	5.26	6.10
5.....	CXOU J031718.4–410633	3 17 18.48	–41 06 33.4	5.21	11.49 $\pm$ 1.93	5.96	7.82
6.....	CXOU J031719.1–410628	3 17 19.12	–41 06 28.1	5.92	19.71 $\pm$ 2.53	7.81	13.42
7.....	CXOU J031718.7–410637	3 17 18.75	–41 06 37.3	9.12	5.33 $\pm$ 1.31	4.06	3.63
8.....	CXOU J031719.4–410629	3 17 19.47	–41 06 29.1	9.95	6.69 $\pm$ 1.47	4.55	4.56
9.....	CXOU J031719.5–410623	3 17 19.55	–41 06 24.0	11.57	5.62 $\pm$ 1.35	4.17	3.83
10.....	CXOU J031718.6–410615	3 17 18.63	–41 06 15.1	13.22	8.23 $\pm$ 1.63	5.05	5.61
11.....	CXOU J031719.2–410641	3 17 19.28	–41 06 41.9	15.63	4.49 $\pm$ 1.20	3.73	3.06
12.....	CXOU J031717.6–410615	3 17 17.65	–41 06 15.9	16.38	7.61 $\pm$ 1.57	4.85	5.18
13.....	CXOU J031719.3–410614	3 17 19.37	–41 06 14.4	16.42	34.04 $\pm$ 3.32	10.26	23.18
14.....	CXOU J031719.1–410609	3 17 19.13	–41 06 09.4	19.84	4.89 $\pm$ 1.26	3.89	3.33
15.....	CXOU J031719.6–410607	3 17 19.68	–41 06 07.7	23.96	12.21 $\pm$ 1.99	6.14	8.31
16.....	CXOU J031718.6–410602	3 17 18.66	–41 06 02.2	26.08	9.76 $\pm$ 1.78	5.49	6.64
17.....	CXOU J031720.7–410641	3 17 20.79	–41 06 41.0	27.85	4.54 $\pm$ 1.21	3.75	3.09
18.....	CXOU J031718.9–410658	3 17 18.96	–41 06 58.7	30.67	3.26 $\pm$ 1.03	3.18	2.22
19.....	CXOU J031717.9–410700	3 17 17.95	–41 07 00.7	33.22	8.33 $\pm$ 1.64	5.08	5.67
20.....	CXOU J031717.3–410558	3 17 17.30	–41 05 58.4	33.28	5.85 $\pm$ 1.38	4.25	3.98
21.....	CXOU J031720.3–410657	3 17 20.39	–41 06 58.0	35.90	4.88 $\pm$ 1.26	3.88	3.32
22.....	CXOU J031715.5–410609	3 17 15.56	–41 06 09.3	39.23	7.33 $\pm$ 1.54	4.76	4.99
23.....	CXOU J031721.7–410651	3 17 21.70	–41 06 51.9	42.24	32.59 $\pm$ 3.25	10.04	22.19
24.....	CXOU J031718.8–410712	3 17 18.82	–41 07 12.0	43.77	11.93 $\pm$ 1.96	6.07	8.12
25.....	CXOU J031715.0–410611	3 17 15.00	–41 06 11.9	43.84	38.40 $\pm$ 3.52	10.90	26.14
26.....	CXOU J031716.9–410709	3 17 16.99	–41 07 09.5	45.02	12.49 $\pm$ 2.01	6.21	8.50
27.....	CXOU J031716.5–410712	3 17 16.52	–41 07 12.7	50.21	15.37 $\pm$ 2.23	6.89	10.47
28.....	CXOU J031717.5–410718	3 17 17.51	–41 07 18.2	51.42	19.85 $\pm$ 2.53	7.83	13.52
29.....	CXOU J031717.5–410724	3 17 17.53	–41 07 24.9	57.81	6.40 $\pm$ 1.44	4.45	4.36
30.....	CXOU J031713.4–410629	3 17 13.46	–41 06 29.6	58.04	9.92 $\pm$ 1.79	5.54	6.75
31.....	CXOU J031723.4–410648	3 17 23.48	–41 06 48.6	58.73	21.63 $\pm$ 2.64	8.18	14.73
32.....	CXOU J031723.2–410709	3 17 23.25	–41 07 09.4	66.75	4.24 $\pm$ 1.17	3.62	2.89
33.....	CXOU J031724.5–410611	3 17 24.57	–41 06 11.2	69.67	6.63 $\pm$ 1.46	4.53	4.52
34.....	CXOU J031721.4–410733	3 17 21.43	–41 07 33.9	73.03	22.39 $\pm$ 2.69	8.32	15.24
35.....	CXOU J031716.6–410512	3 17 16.68	–41 05 12.9	78.46	36.23 $\pm$ 3.42	10.58	24.67
36.....	CXOU J031713.8–410726	3 17 13.82	–41 07 26.1	79.09	34.36 $\pm$ 3.33	10.31	23.40
37.....	CXOU J031725.9–410621	3 17 25.90	–41 06 21.2	82.86	11.33 $\pm$ 1.91	5.92	7.72
38.....	CXOU J031711.5–410714	3 17 11.57	–41 07 14.1	91.65	5.27 $\pm$ 1.31	4.04	3.59
39.....	CXOU J031712.1–410531	3 17 12.10	–41 05 31.3	92.94	6.53 $\pm$ 1.45	4.49	4.45
40.....	CXOU J031719.2–410453	3 17 19.29	–41 04 53.7	94.94	4.83 $\pm$ 1.25	3.87	3.29
41.....	CXOU J031726.3–410544	3 17 26.36	–41 05 44.1	98.22	20.86 $\pm$ 2.60	8.03	14.21
42.....	CXOU J031711.8–410501	3 17 11.89	–41 05 01.1	115.55	3.06 $\pm$ 1.00	3.08	2.09
43.....	CXOU J031722.5–410815	3 17 22.58	–41 08 15.2	115.94	6.67 $\pm$ 1.47	4.54	4.54
44.....	CXOU J031721.7–410434	3 17 21.71	–41 04 34.9	118.76	4.71 $\pm$ 1.23	3.82	3.21
45.....	CXOU J031713.5–410442	3 17 13.54	–41 04 42.5	120.22	4.13 $\pm$ 1.16	3.57	2.81
46.....	CXOU J031724.2–410811	3 17 24.21	–41 08 11.7	121.31	8.43 $\pm$ 1.65	5.11	5.74
47.....	CXOU J031719.0–410423	3 17 19.01	–41 04 23.2	125.15	10.41 $\pm$ 1.83	5.67	7.09
48.....	CXOU J031714.4–410430	3 17 14.45	–41 04 30.2	127.12	3.73 $\pm$ 1.10	3.40	2.54

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Bregman (2001, hereafter SIB01). We modeled unrelated background sources based on *Chandra* deep fields (e.g., Mushotzky et al. 2000); about three such sources are expected in an angular area subtended by the bulge. We first tried a single power-law (plus the background sources) model, but it could be rejected at greater than 99% confidence level. The problem with a single power law is the steep drop above  $\sim 2.5 \times 10^{38} \text{ ergs s}^{-1}$ . Elliptical and S0 galaxies have luminosity functions that are broken power laws, with the break occurring at about this same luminosity (SIB00; Blanton et al. 2001). Thus, we tried such a broken power

law, and it gave an acceptable fit. However, the power-law exponent above the break was very steep; the best-fit exponent was  $-59$ . Thus, the NGC 1291 source luminosity function effectively is cut off above  $\sim 2.5 \times 10^{38} \text{ ergs s}^{-1}$ . We tried fitting the luminosity function as a single power law with a high-luminosity cutoff,

$$\frac{dN}{dL_{38}} = \begin{cases} N_0 \left( \frac{L_{38}}{L_c} \right)^{-\alpha} & L_{38} \leq L_c \\ 0 & L_{38} > L_c \end{cases}, \quad (1)$$

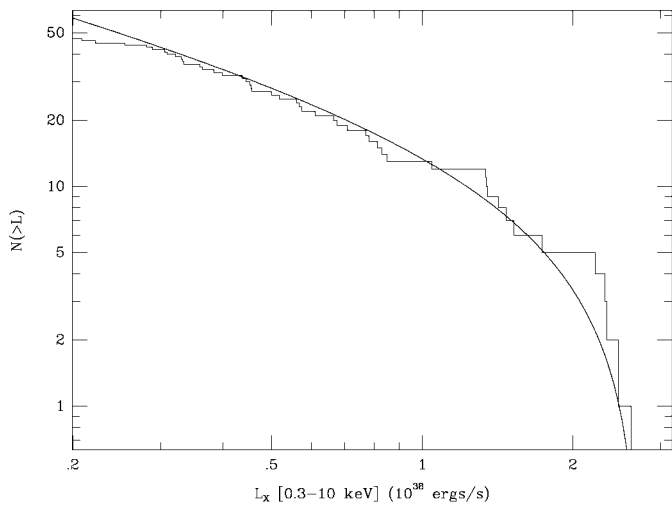


FIG. 3.—Histogram of the cumulative 0.3–10 keV X-ray luminosity function for the 47 point sources within the bulge of NGC 1291 detected in OB1. The central source has been omitted. Roughly three of these sources are expected to be unrelated foreground/background sources. Incompleteness may affect the sources below  $\sim 3 \times 10^{37}$  ergs  $s^{-1}$ . The solid line is the best-fit cutoff power-law function for the galactic sources (eq. [1]).

where  $L_{38}$  is the X-ray luminosity (0.3–10 keV) in units of  $10^{38}$  ergs  $s^{-1}$ , and  $L_c$  is the cutoff luminosity. The best-fit values are  $L_c = 2.6^{+0.2}_{-0.5} \times 10^{38}$  ergs  $s^{-1}$ ,  $\alpha = 1.56^{+0.32}_{-0.53}$ , and  $N_0 = 3.7^{+4.4}_{-0.9}$ . This best-fit cutoff power law is shown in Figure 3.

In Figure 4 we plot the X-ray colors of the point sources found in the OB1+OB2 observation for the 48 sources found within the bulge. We define three X-ray bands, soft S (0.3–1.0 keV), medium M (1.0–2.0 keV), and hard H (2.0–

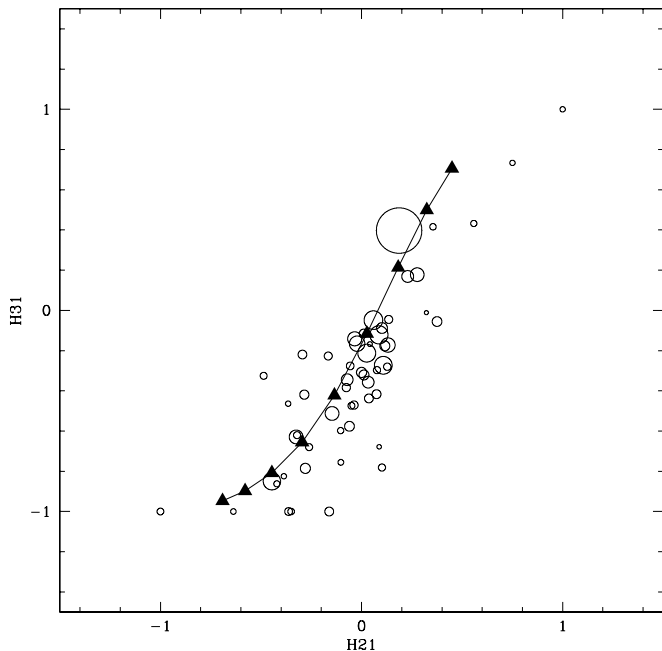


FIG. 4.—X-ray hardness ratios of point sources in NGC 1291, defined as  $H21 = (M-S)/(M+S)$  and  $H31 = (H-S)/(H+S)$ , where S, M, and H are the counts in the 0.3–1.0, 1.0–2.0, and 2.0–6.0 keV energy bands, respectively. The area of the circle is proportional to the total flux of the source. The filled triangles represent the colors predicted from a power-law model with an exponent  $\Gamma = 0$  (upper right) to  $\Gamma = 3.2$  in increments of 0.4.

6.0 keV), and create two X-ray colors,  $H21 = (M-S)/(M+S)$  and  $H32 = (H-S)/(H+S)$ . These are the same bands and colors defined in SIB00, except for the upper energy limit of band H, where we exclude energies above 6.0 keV to reduce noise. This has only a minimal effect on H31. The sources occupy a rather narrow band in color space, as was found for the sources in NGC 4697 and NGC 1553 (SIB01; Blanton et al. 2001). The source located at  $(-1, -1)$  is a supersoft source, similar to those found in the Large Magellanic Cloud and M31 (e.g., Kahabka & van den Heuvel 1997), and has no detectable emission above 1 keV. The colors predicted from a power law with a range of exponents is also shown in Figure 4. The colors of the central source (*largest circle*) indicates a rather hard spectrum although somewhat more band S emission than might be expected. A detailed spectrum of this source is presented in § 4.3. Four sources have H31 values of  $-1$  (no band H emission) and H21 between  $-0.2$  and  $-0.4$ . Three of these sources are on the outskirts of the bulge and might therefore be unrelated to NGC 1291 (a similar population of sources was found at larger radii in NGC 4697; SIB01).

We compared the positions of the X-ray point sources to objects found on the Digitized Sky Survey (DSS) images. None of the 47 noncentral point sources in the bulge of NGC 1291 have optical counterparts that are detectable on the DSS images. However, this is not surprising since faint optical sources would be difficult to detect in the high optical surface brightness bulge. Of the 43 sources outside the bulge, only three had optical counterparts within  $3''$ , whose coordinates were obtained from the USNO-A2.0 optical catalog (Monet et al. 1998). All three optical sources were very red and might be globular clusters belonging to NGC 1291. A significantly higher percentage of the X-ray sources in the outer regions of NGC 4697 and NGC 1553 are potentially associated with a globular cluster than was found for NGC 1291. However, the studies of NGC 4697 and NGC 1553 benefited from globular cluster lists derived from ground-based or *Hubble Space Telescope* data, so it was possible to identify fainter candidate globular clusters. We were unable to find a globular cluster list for NGC 1291 in the literature, and it is likely that several more of the X-ray sources detected in the outer regions of NGC 1291 also belong to globular clusters.

### 3.3. Diffuse Emission

Since the soft-band X-ray emission is roughly circularly symmetric, we extracted a radial surface brightness profile in circularly concentric annular rings centered on the center of NGC 1291 and excluded all point sources detected at the greater than  $3\sigma$  level. The soft-band emission was detectable out to a radius of  $120''$ , after which the emission flattened to a constant value. We chose an annular region  $140''$ – $170''$  in extent as our background region, being sure to omit the part of this region that was not covered by both observations. The raw and the background-subtracted surface brightness profiles for the soft band are shown in Figure 5.

XSPEC simulations show that 0.32 keV gas (which describes the spectrum of the soft emission; see § 4.2 below) emits a negligible amount of flux above 1.5 keV. Therefore, we can safely assume that the diffuse hard emission is from unresolved point sources below the detection threshold of the observation. In fact, extrapolating the luminosity func-

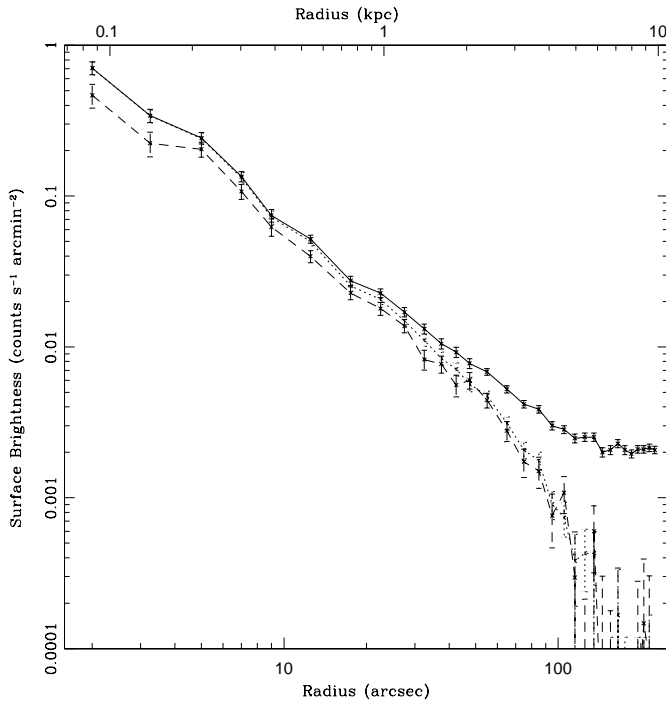


FIG. 5.—Radial surface brightness of the diffuse emission in the 0.3–1.0 keV band, showing the raw profile (*solid line*), background-subtracted profile (*dotted line*), and unresolved source-corrected profile (*dashed line*).

tion (see § 3.2) of the resolved sources down to  $10^{35}$  ergs  $s^{-1}$  predicted a value for the luminosity for the unresolved sources that was within 4% of the measured value for the diffuse hard emission. The diffuse emission in the soft band, however, is a combination of hot gas and unresolved sources. We can use the observed radial profile of the 1.5–6 keV emission to correct the 0.3–1.0 keV radial profile for stellar contamination. We assume that the ratio of 0.3–1.0/1.5–6.0 keV count flux is the same for the unresolved point sources as it is for the resolved point sources, and we multiply the hard radial profile by this ratio before subtracting it from the soft radial profile to yield the gas-only radial profile. This profile is also shown in Figure 5. We fit a  $\beta$ -profile to the gaseous surface brightness distribution and find best-fit values of  $\beta = 0.45^{+0.02}_{-0.01}$  and  $r_{\text{core}} = 2''.9^{+1.1}_{-0.9}$  ( $0.125^{+0.043}_{-0.039}$  kpc) (Fig. 6). A value of  $\beta = 0.45$  is typical for elliptical galaxies (Forman et al. 1985; Trinchieri et al. 1986). Previous studies of elliptical galaxies have found much larger core radii than was found for NGC 1291. However, all these galaxies were quite large, luminous, and rich in hot gas. A recent *ROSAT* HRI analysis of several smaller, X-ray faint galaxies, found core radii similar to the value found here (Brown & Bregman 2001).

We extracted the surface brightness profile of the unresolved emission in the 1.5–6 keV band in elliptically concentric rings that followed the optical light of the galaxy and found that the diffuse hard X-ray emission was distributed like the optical light (de Vaucouleurs 1975). This is consistent with the idea that the diffuse hard X-ray emission emanates from LMXBs with luminosities below the detection threshold. We also determined the ratio of counts in the 0.7–1.0 keV band to the counts in the 0.3–0.7 keV band (Fig. 7). The ratio decreases steeply with radius out to  $15''$ , and declines more slowly at larger radii. This decline repre-

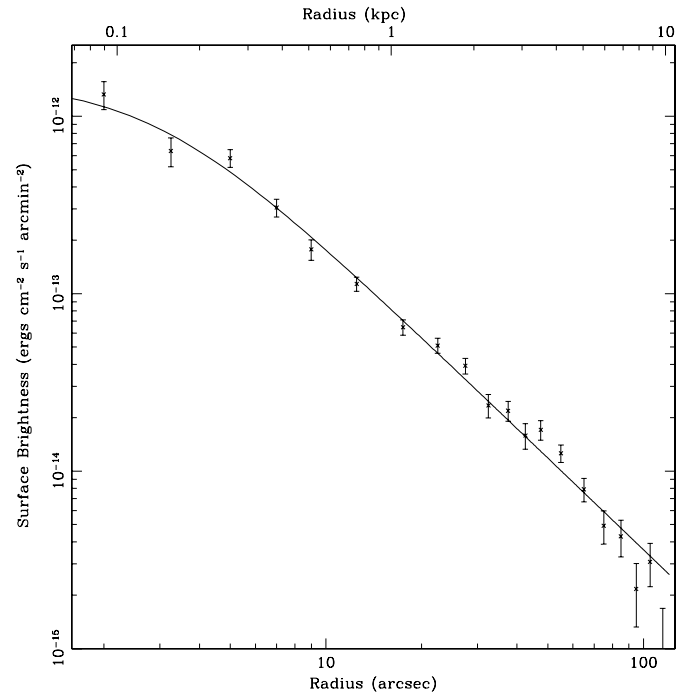


FIG. 6.—Radial surface brightness of gaseous emission in NGC 1291, with best-fit  $\beta$ -profile  $\beta = 0.45$  and  $r_{\text{core}} = 2''.9$  (125 pc).

sents either a decline in temperature or a decline in metallicity and will be investigated further in § 4.2.

#### 4. SPECTRAL ANALYSIS

Previous *Chandra* studies have found that the calibration of the ACIS-S chip is currently suspect below 0.7 keV (Mar-

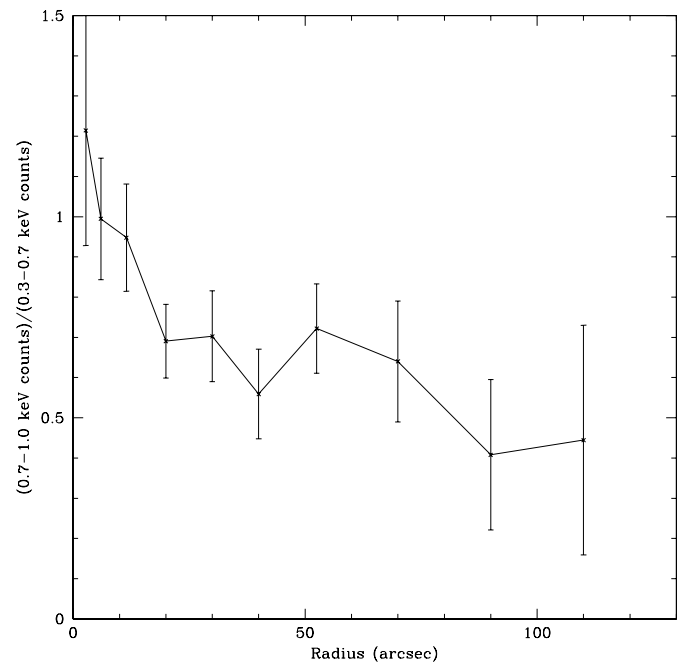


FIG. 7.—Ratio of 0.3–0.7 keV counts to 0.7–1.0 keV counts as a function of radius ( $1\sigma$  uncertainties). The softening of the spectrum with radius indicates a decrease in temperature or a decrease in metallicity, or both.

kevitch et al. 2000; SIB01), so we initially fitted all spectra only in the 0.7–10 keV energy range. However, it was found that the best-fit 0.7–10 keV spectrum of the point sources provided an adequate fit to the spectrum even when channels down to an energy of 0.5 keV were added. Therefore, we include channels down to 0.5 keV in all subsequent fits. For the diffuse emission, we limited the spectral range to 0.5–6.0 keV to eliminate high background rates at high energies. Background was once again taken from an annular region 140''–170'' in extent. The spectra were regrouped so that each channel contained at least 25 counts. Spectra were extracted from OB1 and OB2 separately and fitted within XSPEC 11.0 separately. Redistribution matrix files (RMF) and auxiliary response files (ARF) were created using the CALCRMF and CALCARF routines of Alexey Vikhlinin for extended sources and with the CIAO task PSEXTRACT for the central point source. All errors given are 90% confidence levels for one interesting parameter ( $\Delta\chi^2 = 2.71$ ). A summary of the spectral fits is given in Table 2.

#### 4.1. Summed Resolved Point Sources in the Bulge

In order to avoid excessive contamination from unrelated foreground/background X-ray sources and from disk/spiral arm population X-ray sources of NGC 1291, we analyze only those sources projected within the bulge of the galaxy. We also excluded the central source that is most likely an AGN. As noted above (§ 3.2), we would expect only  $\sim 3$  serendipitous foreground/background sources above our detection threshold within the bulge. A simple bremsstrahlung model with a temperature of  $kT = 7.5^{+1.6}_{-1.2}$  keV and the absorption fixed at the Galactic value ( $1.60 \times 10^{20} \text{ cm}^{-2}$ ) fitted the data adequately ( $\chi^2_{\nu} = 1.17$  for 112 degrees of freedom [dof]). A power-law model provided a somewhat better fit ( $\chi^2_{\nu} = 1.06$  for 112 dof) with  $\Gamma = 1.56 \pm 0.05$ . A disk blackbody+blackbody model that has been employed to fit the spectra of Galactic LMXBs as well as the summed emission from LMXBs in M31 (Mitsuda et al. 1984) provided an equally acceptable fit ( $\chi^2_{\nu} = 1.06$ ), but the best-fit parameters ( $kT_{\text{in}} = 0.37$  keV and  $kT_{\text{BB}} = 1.1$  keV) were unlike those of Galactic LMXBs. Freeing the absorption did not improve the fit. The power-law exponent and the brems-

strahlung temperature are in agreement with previous *Chandra* observations of LMXBs in early-type systems (SIB01; Blanton et al. 2001). No excess soft emission was detected in the spectra of the LMXBs. The summed source fluxes from OB1 and OB2 were consistent within the uncertainties, indicating that the effect of variability of the summed source spectrum is small.

#### 4.2. Diffuse Emission

The color analysis of the diffuse emission within the bulge indicated the presence of both stellar and gaseous components in the diffuse emission, so we used a two-component model consisting of a MEKAL component (Mewe, Gronenschild, & van den Oord 1985; Kaastra & Mewe 1993; Liedahl, Osterheld, & Goldstein 1995) to represent the gaseous emission and a power law or thermal bremsstrahlung to represent the unresolved stellar sources. The hard-component parameter ( $\Gamma$  or  $kT$ ) was fixed at the value found for the sum of the resolved sources. The temperature and metallicity of the MEKAL component were allowed to vary. A good fit ( $\chi^2_{\nu} = 1.08$  for 170 dof) was obtained with a temperature of  $0.32^{+0.04}_{-0.03}$  keV and metallicity of  $0.06 \pm 0.02$  solar when the hard component was a power-law model. Nearly identical values were found when a bremsstrahlung or disk blackbody+blackbody model represented the hard component. The temperature and abundance values were practically independent of the shape of the hard component. Fixing the exponent of the power law at  $\Gamma = 1$  or  $\Gamma = 2$  led to less than a 5% change in the best-fit temperature.

Next we extracted spectra from annular regions 1''5–15'' and 15''–100'' in extent and fitted them with a similar model as above. From the inner bin to the outer bin, the temperature declined very slightly from  $0.34^{+0.05}_{-0.03}$  keV to  $0.30^{+0.04}_{-0.03}$  keV. Interestingly, there was some evidence for decreasing abundance with radius from  $0.13 \pm 0.04$  to  $0.05^{+0.04}_{-0.02}$  of the solar value.

#### 4.3. Central Point Source

The spectrum from the bright central point source could not be fitted well with any single component model in the 0.5–10 keV energy range. However, the emission within the

TABLE 2  
X-RAY SPECTRAL FITS

Component	Model	$N_{\text{H}}$ ( $\times 10^{20} \text{ cm}^{-2}$ )	$kT$ or $\Gamma$ (keV)	Abundance ( $Z_{\odot}$ )	Counts/ $\chi^2_{\nu}$ /dof
Sources .....	Bremss	(1.60)	$7.5^{+1.6}_{-1.2}$		3494/1.17/112
Sources .....	Bremss	<0.64	$8.9^{+2.1}_{-1.6}$		3494/1.11/111
Sources .....	Power	(1.60)	$1.56 \pm 0.05$		3494/1.06/112
Sources .....	Power	<3.08	$1.55 \pm 0.08$		3494/1.07/111
Gaseous (global) .....	MEKAL	(1.60)	$0.32^{+0.04}_{-0.03}$	$0.06 \pm 0.02$	3111/1.04/170
Gaseous (global) .....	MEKAL	<8.34	$0.33^{+0.04}_{-0.03}$	$0.06^{+0.08}_{-0.03}$	3111/1.04/169
Gaseous (1''5–15'') .....	MEKAL	(1.60)	$0.34^{+0.05}_{-0.03}$	$0.13 \pm 0.04$	1033/1.59/34
Gaseous (15''–100'') .....	MEKAL	(1.60)	$0.30^{+0.04}_{-0.03}$	$0.05^{+0.04}_{-0.02}$	2078/1.14/155
Central source <sup>a</sup> .....	Power	$203.3^{+74.1}_{-69.3}$	$1.93^{+0.37}_{-0.28}$		826/0.68/48
Central source <sup>a</sup> .....	Bremss	$159.4^{+49.9}_{-48.3}$	$8.3^{+8.3}_{-3.4}$		826/0.68/48
Central source <sup>b</sup> .....	MEKAL	(1.60)	$0.75^{+0.12}_{-0.11}$	$0.09 \pm 0.04$	1228/0.76/70
Central source <sup>b</sup> .....	Blackbody	(1.60)	$0.21 \pm 0.03$		1228/0.86/70

<sup>a</sup> 1.5–10 keV only, with normalizations free for OB1 and OB2.

<sup>b</sup> 0.5–10 keV; soft component parameters, after fixing the parameters of the power-law component derived in the 1.5–10 keV fit.



1"5 extraction radius is likely contaminated by  $\sim 0.34$  keV gaseous emission. Therefore, we fitted the spectrum of the central source only over the 1.5–10 keV range where the gaseous emission is negligible. Now the spectrum is fitted equally well by a heavily absorbed power law ( $\Gamma = 1.93^{+0.37}_{-0.28}$  and  $N_{\text{H}} = 2.03^{+0.74}_{-0.69} \times 10^{22}$  cm $^{-2}$ ) or thermal bremsstrahlung ( $kT = 8.3^{+8.3}_{-3.4}$  keV and  $N_{\text{H}} = 1.59^{+0.50}_{-0.48} \times 10^{22}$  cm $^{-2}$ ). The power-law exponent/bremsstrahlung temperature and the absorption were linked for OB1 and OB2, and allowing them to vary separately did not significantly improve the fit. These values are quite unlike those of the summed noncentral point source spectrum in NGC 1291, which was fitted well by a thermal model of similar temperature but with only Galactic absorption. The 2–10 keV luminosity of the central source decreased by a factor of 2 between OB1 and OB2, from  $2.9 \times 10^{39}$  to  $1.4 \times 10^{39}$  ergs s $^{-1}$  (for the power-law model). The high variability, a power-law index of 1.7–2.0, and heavy ( $10^{22}$  cm $^{-2}$ ) absorption argues that the source is an obscured low-luminosity AGN.

After freezing the best-fit parameters, we included channels down to 0.5 keV and noticed excess emission in the 0.5–1.5 keV range (Fig. 8). A total of 285 counts were found in excess of the absorbed power-law model. Below 1.0 keV the count rates of OB1 and OB2 were the same, indicating a different source of the soft emission than what is producing the variable hard emission. The number of counts below 1.5 keV that is expected within the 1"5 extraction region from the hot gas (by extrapolating the surface brightness profile of the hot gas to the very center) is only  $\sim 50$  counts. Thus, most of the excess counts must come from a second, soft component of the central source. After fixing the absorption and power-law exponent, we added a MEKAL component with a temperature of 0.34 keV to model the hot ISM gas expected in the 1"5 extraction region, and fixed the normalization so that this component yielded 50 counts. We then added another MEKAL model and allowed the temperature and metallicity to vary. This component was absorbed by a column density equal to the Galactic column density in that direction. The best-fit MEKAL temperature was  $kT = 0.75^{+0.12}_{-0.11}$  keV and the best-fit metallicity was

$0.09 \pm 0.04$  solar ( $\chi^2_{\nu} = 0.76$  for 69 dof). Substituting a blackbody model for the second MEKAL model yielded a somewhat worse but still acceptable fit with  $kT_{\text{BB}} = 0.21 \pm 0.03$  keV. The luminosity of the soft component was  $1.5 \times 10^{38}$  ergs s $^{-1}$ , or 5%–10% of the hard-component luminosity.

## 5. DISCUSSION

### 5.1. A Comparison of the Stellar $L_{\text{X}}/L_{\text{B}}$ Ratio of NGC 1291, NGC 4697, and NGC 1553

Previous work has indicated that the stellar X-ray-to-optical luminosity ratio is not the same in all galaxies. In a survey of 61 early-type galaxies observed by *ROSAT*, Irwin & Sarazin (1998b) found that eight galaxies had extremely low  $L_{\text{X}}/L_{\text{B}}$  values, over a factor of 3 less than the  $L_{\text{X}}/L_{\text{B}}$  value of the bulge of M31 and other X-ray faint early-type galaxies whose X-ray emission we now know to be composed primarily of LMXBs with only a small amount of gas such as NGC 4697 (Primini, Forman, & Jones 1993; Shirey et al. 2001; SIB01). If all the gas were removed from NGC 4697, for example, its  $L_{\text{X}}/L_{\text{B}}$  ratio would decrease by only a factor of  $\sim 1.4$  in the *ROSAT* band. Since eight galaxies in the Irwin & Sarazin (1998b) sample had  $L_{\text{X}}/L_{\text{B}}$  values at least a factor of 3 below that of M31 or NGC 4697, this implies that the production of LMXBs in early-type systems is different from galaxy to galaxy, and that the X-ray luminosity from stellar sources does not scale linearly with the optical luminosity. The spatial resolution of *ROSAT* was too coarse to test this hypothesis directly, since individual LMXBs could not be resolved. It was not known if the discrepancy in the LMXB population resulted from a lack of LMXBs at all luminosities or just at the high end of the luminosity distribution.

*Chandra's* superb spatial resolution allows us to distinguish between the two scenarios. The total (resolved plus unresolved) stellar  $L_{\text{X}}/L_{\text{B}}$  value for NGC 1291 is estimated to be  $5.3 \times 10^{29}$  ergs s $^{-1} L_{\odot}^{-1}$  (of which 71% is resolved in our observation). In the 0.5–2.0 keV (*ROSAT*) band, this stellar  $L_{\text{X}}/L_{\text{B}}$  value is  $1.5 \times 10^{29}$  ergs s $^{-1} L_{\odot}^{-1}$ . Using the source list as well as the estimated emission from unresolved point sources from the *Chandra* observation of NGC 4697 (SIB01), we found the total stellar  $L_{\text{X}}/L_{\text{B}}$  value for NGC 4697 within one effective (half-optical light) aperture was  $7.5 \times 10^{29}$  ergs s $^{-1} L_{\odot}^{-1}$  (it is easiest to deal only with sources within the effective aperture in large galaxies like NGC 4697, since the number of contaminating serendipitous sources is much smaller within this angular region than from over the entire optical extent of the galaxy). A similar exercise within two effective radii for NGC 1553 (Blanton et al. 2001) yielded a value of  $7.2 \times 10^{29}$  ergs s $^{-1} L_{\odot}^{-1}$ . In all three galaxies, the central source was omitted. From the luminosity distribution function of NGC 1291 (Fig. 3) it is apparent that this difference can be attributed to a lack of bright sources in NGC 1291. In fact, there are no sources in NGC 1291 brighter than  $3 \times 10^{38}$  ergs s $^{-1}$ . Direct comparison with NGC 4697 and NGC 1553 indicates that the lack of sources above  $3 \times 10^{38}$  ergs s $^{-1}$  in NGC 1291 is probably not the result of low number statistics. Within the inner effective apertures of NGC 4697 and NGC 1553, there are 10 sources each with luminosities greater than  $3 \times 10^{38}$  ergs s $^{-1}$  (neglecting central sources that might be AGNs). Given that the ratio of optical luminosities within the effective

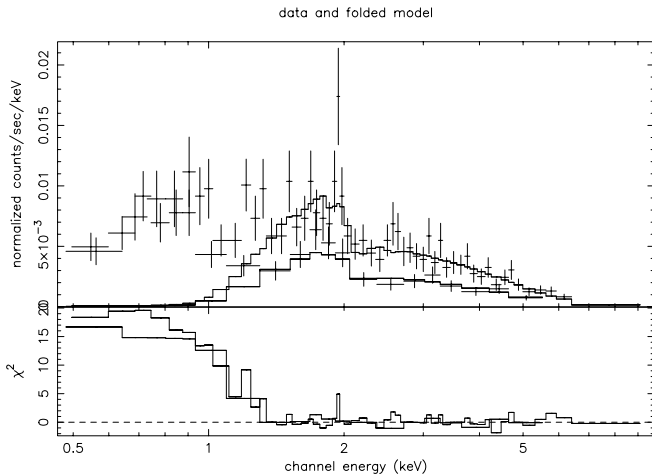


Fig. 8.—Best-fit power-law spectrum of the central point source from OB1 and OB2 over the 1.5–10 keV range. Energy channels below 1.5 keV have been added without refitting the spectrum to illustrate the excess soft emission. Note that although the power-law component differs by a factor of 2 between OB1 and OB2, the excess soft component flux is the same between the two observations.

aperture of NGC 4697 and NGC 1553 to the optical luminosity of the entire bulge of NGC 1291 is 1.17 and 2.34, respectively, we would expect 3.7–7.3 sources in NGC 1291 above this luminosity. If we include all sources detected in the field, the number of sources above this luminosity grows to 19 and 35 for NGC 4697 and NGC 1553, respectively, again predicting  $\sim 7$  sources in the bulge of NGC 1291. In NGC 4697, NGC 1553, and NGC 1399 (R. Mushotzky & L. Angelini 2000, private communication) there was a break or “knee” in the luminosity distribution function around a luminosity of  $3 \times 10^{38}$  ergs  $s^{-1}$ . This luminosity is also approximately the Eddington luminosity of a  $1.4 M_{\odot}$  neutron star. SIB00 suggest that this break represents a division between LMXBs with black hole and neutron star accreters. If this interpretation is correct, it would mean that NGC 1291 does not have any black hole binaries accreting near the Eddington limit. It is worth noting that the inner  $5'$  of the bulge of the spiral galaxy M31 also does not contain any X-ray source more luminous than  $3 \times 10^{38}$  ergs  $s^{-1}$  (Primini et al. 1993; after converting their 0.2–4.0 keV luminosity to 0.3–10 keV luminosity).

Another illustrative way of presenting the luminosity distribution function is shown in Figure 9a, where we have plotted the cumulative  $L_X/L_B$  value of sources in the galaxy as a function of increasing  $L_X$ . Since we have normalized the X-ray luminosity of the sources by the optical luminosity of the galaxy, we can now compare the curve to those of other galaxies. Figure 9a also shows the same quantity for the inner effective aperture of NGC 4697 and within two effective radii for NGC 1553. Note that the  $y$ -intercept of each curve represents the *unresolved* source  $L_X/L_B$  value, a quantity set by the limiting luminosity of the observation (i.e., the curves would go to zero if every last faint LMXB could be detected). Since the determination of  $L_B$  is crucial

in this comparison, we did not attempt to gauge  $L_B$  from the bulge assuming a specific bulge-disk decomposition for NGC 1291. Instead we only included X-ray sources within a circular aperture of  $131''$ , for which the integrated  $B$  magnitude within this aperture was 10.13 (using photometry values listed in the compilation of Prugniel & Heraudeau 1998). The Galactic reddening maps of Schlegel, Finkbeiner, & Davis (1998) indicated an absorption of  $A_B = 0.056$  mag. Correcting for foreground reddening and assuming a distance of 8.9 Mpc, we determined an optical luminosity of  $1.08 \times 10^{10} L_{\odot}$ . Schlegel et al. (1998) claim a mean uncertainty of 16% of  $A_B = 0.056$ , or 0.009 mag. This amounts to only a 1% uncertainty in  $L_B$  that results from uncertainties associated with foreground extinction corrections.

Two striking features stand out in Figure 9a. The total cumulative  $L_X/L_B$  value of NGC 1291 is a factor of 1.4 less than NGC 4697 and NGC 1553. As mentioned above, this is the result of a lack of very luminous sources in NGC 1291. This is surprising considering the optical characteristics of early-type systems are very similar. However, for some reason NGC 1291 does not have any of the brightest (probable) black hole binaries that other galaxies have. All three galaxies show a substantial spread in the number and luminosity of sources above  $3 \times 10^{38}$  ergs  $s^{-1}$ , the break luminosity discussed above. Also, below  $10^{38}$  ergs  $s^{-1}$  the slope of the cumulative  $L_X/L_B$  values of NGC 1291 and NGC 4697 are quite similar (NGC 1553 is too distant and the observation time was too short to test this with this galaxy too). In fact, if the distance to NGC 4697 is changed from 15.9 Mpc (the distance assumed by SIB01, which is the recessional velocity distance determined using a value of  $H_0 = 50$  km  $s^{-1}$  Mpc $^{-1}$ ; Faber et al. 1989) to 11.7 Mpc (the distance implied by the surface brightness fluctuation method; Tonry et al.

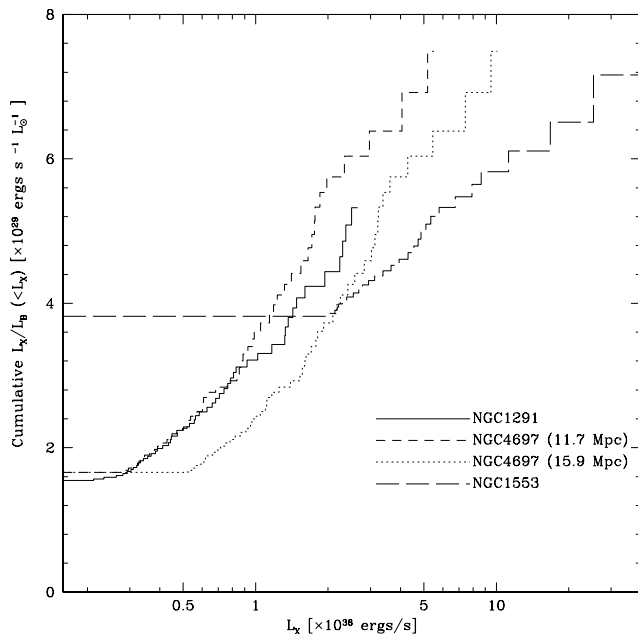


FIG. 9a

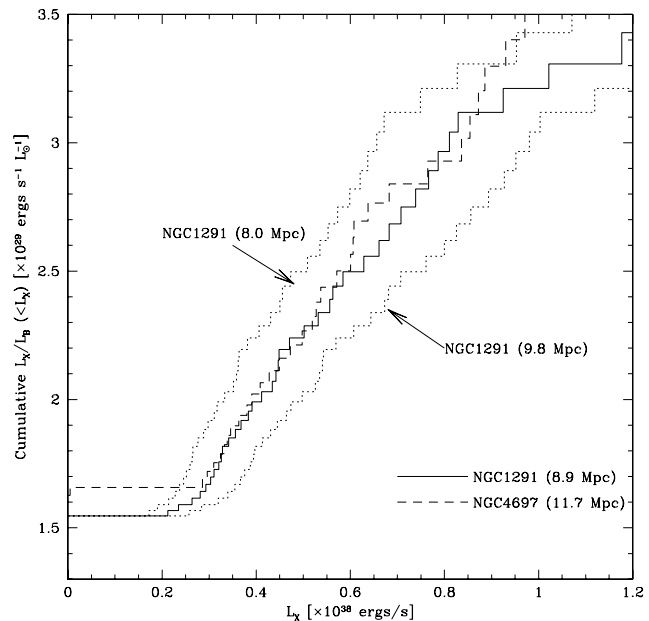


FIG. 9b

FIG. 9.—(a) Cumulative  $L_X/L_B$  values as a function of increasing  $L_X$  for LMXBs in NGC 1291, NGC 4697 (for distances of 15.9 and 11.7 Mpc), and NGC 1553. Note the disparity in the number of high-luminosity LMXBs among the three galaxies. (b) A closer view of the lower left corner of (a), showing the agreement in the cumulative  $L_X/L_B$  value of LMXBs in NGC 1291 and NGC 4697 (when a distance of 11.7 Mpc is chosen). Changing the distance of NGC 1291 by  $\pm 10\%$  destroys this agreement, and suggests that this agreement might be used as a relative distance indicator.

2001), the agreement in the cumulative  $L_X/L_B$  profiles of NGC 1291 and NGC 4697 at low luminosities is remarkable. This indicates that the number of faint LMXBs agrees quite well between the two galaxies if the smaller distance for NGC 4697 is adopted.

The discrepancy in the number of luminous sources in NGC 1291 can be reconciled with those of NGC 4697 and NGC 1553 if we assume a larger distance to NGC 1291 than 8.9 Mpc. If we increase the distance by 40% to 12.5 Mpc, we find nine sources above  $3 \times 10^{38}$  ergs  $s^{-1}$ . However, this creates another problem. Although the total cumulative  $L_X/L_B$  value is independent of distance, the curve shifts to the right when the distance is increased. When the distance to NGC 1291 is changed from 8.9 Mpc, the agreement in the cumulative  $L_X/L_B$  value below  $10^{38}$  ergs  $s^{-1}$  is destroyed. Regardless of the chosen distance, the data conclusively show that the production of LMXBs in NGC 1291 differs from that in NGC 4697. If the distance is set to match the low end of the luminosity distribution function, too few bright sources are produced in NGC 1291. If the distance is set to match the high end, too few fainter ( $<10^{38}$  ergs  $s^{-1}$ ) sources are produced in NGC 1291. Moreover, the shape of the upper end of the luminosity function of NGC 1291 disagrees with that of NGC 4697 (§ 3.2), independent of the distance.

Assuming the distances of 8.9 and 11.7 Mpc to NGC 1291 and NGC 4697, respectively, are correct, the excellent agreement in the cumulative  $L_X/L_B$  value below  $10^{38}$  ergs  $s^{-1}$  between NGC 1291 and NGC 4697 (Fig. 9a) suggests that this feature can be used to estimate the distance to nearby galaxies. If the cumulative  $L_X/L_B$  value below  $10^{38}$  ergs  $s^{-1}$  is a constant from galaxy to galaxy, the point where the cumulative  $L_X/L_B$  value begins to diverge might be used as a standard candle. Using X-ray binaries as a standard candle is not a new concept. Margon & Ostriker (1973) suggested that the luminosity of X-ray sources in galaxies could be limited by the Eddington luminosity based on observations of X-ray sources in the Local Group. More recently, SIB00 suggested that the break in the luminosity distribution function at  $3 \times 10^{38}$  ergs  $s^{-1}$  might be used as a distance indicator too. The accuracy of this method, however, would always be limited by the relatively small number of sources above the break. The statistics on sources below the break are generally much better and are further improved by summing up the luminosities. What is required observationally is to resolve the luminosity function down to  $\lesssim 10^{38}$  ergs  $s^{-1}$  and to determine accurately the total amount of X-ray emission from unresolved sources. This method could be used in conjunction with the break in the luminosity function method of SIB00 for greater accuracy. Figure 9b zooms in on the lower left corner of Figure 9a, illustrating how sensitive the cumulative  $L_X/L_B-L_X$  relation is to distance. Changing the assumed distance of NGC 1291 by  $\pm 10\%$  leads to an easily measurable difference in the cumulative  $L_X/L_B$  values of NGC 1291 and NGC 4697. Of course, claims of the validity of this method are premature considering that only two galaxies have been tested thus far. Many more galaxies will need to be compared to NGC 1291 and NGC 4697 to confirm this method. However, should this method be valid, distances to nearby galaxies can be determined to better than 10% accuracy and would be one of the very few nonoptical methods for determining distances to galaxies. We point out that the cumulative  $L_X/L_B$  method is a relative distance estimator, while the method using the

break in the luminosity function is an absolute distance estimator. Admittedly, the distance to NGC 1291 is not known with great accuracy, but if this distance estimator method works, we can determine accurate relative distances to these galaxies. In future work, we will study galaxies for which multiple distance estimators already exist and agree with one another and apply our method to them. Also useful will be galaxies that are known to be at the same distance (owing to their group membership).

Recently, R. White, S. Kulkarni, & C. Sarazin (2002, in preparation) have found a correlation between the total LMXB  $L_X/L_B$  value and the specific frequency of globular clusters in a galaxy. In addition, Angelini, Loewenstein, & Mushotzky (2001) found that 70% of the X-ray point sources found in a portion of NGC 1399 for which *Hubble* data existed were coincident with globular clusters of NGC 1399. Both these results would seem to be at odds with the idea that the cumulative  $L_X/L_B$  profile below  $10^{38}$  ergs  $s^{-1}$  is uniform from galaxy to galaxy. One might expect  $L_X$  to scale with the globular cluster specific frequency in addition to the optical luminosity  $L_B$  rather than  $L_B$  alone, rendering the distance estimator method useless in its current form. However, it is possible that both theories are correct. It is known that the specific frequency of globular clusters decreases with decreasing radius in galaxies (Forbes et al. 1996), indicating that the spatial distribution of the globular clusters is more extended than the optical light. For example, the specific frequency of globular clusters in NGC 3115 decreases from  $3.1 \pm 0.5$  to  $1.3 \pm 0.1$  in moving from the outer to the inner regions of the galaxy (Kundu & Whitmore 1998). Therefore, globular cluster X-ray sources might be relatively rare in the inner regions of elliptical galaxies (or bulges), while comprising a larger percentage of the X-ray source population at larger radii (20% in the case of NGC 4697; SIB01). If this is the case, galaxies with high globular cluster specific frequencies would have higher  $L_X/L_B$  values than galaxies with low globular cluster specific frequencies because of a higher number of globular cluster X-ray sources at large radii. At smaller radii (such as within the bulge or one effective radius of a galaxy) where nonglobular cluster X-ray sources dominate, the  $L_X/L_B$  value might be a constant from galaxy to galaxy, allowing the distance indicator method to be utilized. A search for globular clusters in the inner regions of elliptical galaxies with *Hubble Space Telescope* would be useful in definitively determining the significance of globular cluster X-ray sources to the total LMXB population and resolving this issue.

### 5.2. The Hot Gas within NGC 1291

The ability to separate the stellar emission from gaseous emission has only become possible since the launch of *Chandra*. Whereas in X-ray bright galaxies the contribution from LMXBs is minimal, such a separation becomes important as the gaseous component becomes less dominant. For example, the *ROSAT* PSPC spectrum of NGC 1291 could be fitted equally well with a two-component Raymond-Smith+bremsstrahlung model with  $kT_{RS} = 0.15$  keV,  $Z = Z_\odot$ , and  $kT_{\text{brem}} = 1.07$  (Bregman et al. 1995) as it could with just a Raymond-Smith model with  $kT_{RS} = 0.55$  keV and  $Z = 0.01 Z_\odot$  (Read, Ponman, & Strickland 1997). In both cases, the inability of *ROSAT* to resolve out the binaries and especially the luminous, highly absorbed AGN leads to an erroneous measurement of the temperature of

the diffuse hot gas. Inaccuracies in the temperature and flux of the hot gas subsequently adversely affect the determination of quantities such as the  $L_{X,\text{gas}}-L_B$  relation and the  $kT_{\text{gas}}-\sigma$  relation, both of which have been used to characterize the history and evolution of the hot gas within early-type systems.

Given the spectral and spatial results above, we conclude that 33% (41%) of the counts and 14% (27%) of the 0.3–10 keV (0.3–2 keV) luminosity emanates from a truly diffuse, gaseous component. The 0.3–10 keV X-ray luminosity of the gas is  $1.4 \times 10^{39}$  ergs  $\text{s}^{-1}$ , leading to a gaseous  $L_X/L_B$  value of  $1.3 \times 10^{29}$  ergs  $\text{s}^{-1} L_\odot^{-1}$ . Such a value is quite low compared to X-ray bright elliptical galaxies but similar to the values found for X-ray faint elliptical galaxies and the bulge of M31 (SIB01; Shirey et al. 2001). Given the velocity dispersion of the bulge of NGC 1291 of 162 km  $\text{s}^{-1}$  (Dalle Ore et al. 1991), the derived temperature of the gas of 0.32 keV falls very close to the best-fit  $kT_{\text{gas}}-\sigma$  relation of Davis & White (1996) but considerably above the best-fit relation of Brown & Bregman (1998). The measured temperature is well above the temperature predicted from the velocity dispersion of 0.17 keV, if the thermal energy of the gas were equal to the kinetic energy of the random motions of the stars.

The  $\beta$ -model for the surface brightness profile of the gas can be inverted to obtain the density profile,  $n(r) = n_0[1 + (r/r_{\text{core}})^2]^{-3\beta/2}$ . Using the best-fit values of the gaseous surface brightness profile of  $\beta = 0.45$  and  $r_{\text{core}} = 2''.9$ , we derive a central electron density of  $n_0 = 0.28 \text{ cm}^{-3}$ . This value is quite high when compared to values obtained for early-type systems with previous instruments (e.g., Rangarajan et al. 1995). However, the  $0''.5$  spatial resolution of *Chandra* coupled with the nearness of NGC 1291 allows us to probe the electron density profile on the scale of  $\sim 50$  pc (note that at the distance of the Virgo Cluster the core radius would be only  $1''.3$ , far below the resolution limit of previous X-ray telescopes). The implied mass of the gas (assuming a volume filling factor of 1) within a radius of  $120''$  is  $5.8 \times 10^7 M_\odot$ . This value is substantially smaller than the derived gas masses of big bright elliptical galaxies, which tend to be as high as  $10^{11} M_\odot$ . The cooling time of the gas at the center of the galaxy is  $1.2 \times 10^7$  yr and remains less than a Hubble time out to the extent to which the gaseous emission can be detected ( $120''$ ).

Given the relative isolation of NGC 1291, it would appear that the lack of a substantial amount of X-ray-emitting gas in the bulge is not the result of recent interaction with a cluster or another galaxy. This result is in accordance with the findings of Brown & Bregman (2000) that optically less luminous galaxies in lower density environments are X-ray faint. In smaller galaxies (or bulges) in noncluster environments, supernova-driven winds can clear the system of much of the gas that might have been pressure-contained by intracluster gas had the galaxy resided in a cluster environment.

Finally, the metallicity of the hot gas in early-type systems has been a long-standing controversy. Optical measurements of the metallicity of stars indicate abundances of solar or greater in elliptical galaxies and the bulges of spiral galaxies. Yet many measurements of the metallicity of the X-ray gas, particularly those determined with *ASCA*, have yielded values of the metallicity of  $\lesssim 20\%$  for many galaxies. Several explanations have been set forth to account for this discrepancy. Buote (1999) suggests that the low measured

metallicity of the X-ray gas with *ASCA* is an artifact of fitting the spectra with isothermal models. Multitemperature models, either owing to local multiphase gas or a temperature gradient, would result in higher abundances, at least in the case of the brightest X-ray elliptical galaxies. Finoguenov & Jones (2000) also point out that the angular scales of the optical and X-ray metallicity are different; whereas integrated optical metallicities are typically measured within an arcminute or less for galaxies at the distance of Virgo, X-ray measurements are typically averaged over  $\sim 3'$  bins. Given that the optically determined metallicities often decline significantly with radius (Carollo, Danziger, & Buson 1993), the stellar metallicity might actually be subsolar at large distances for the center of the galaxy. Furthermore, the *Chandra*-determined abundance profile of the elliptical galaxy NGC 4374 peaked toward the center to a value of  $0.6 Z_\odot$  within a 0.5–5 kpc annulus, and declined at larger radii (Finoguenov & Jones 2001). Both the multicomponent temperature argument and the mismatch of angular size argument seem to resolve the discrepancy between the metallicity measurements in the much-studied X-ray bright early-type galaxies. However, neither explain the low metallicity found here for NGC 1291. The metallicity from the  $1''.5\text{--}15''$  annulus is only  $0.13 \pm 0.04$  solar. An optical measurement of the metallicity of the bulge found it to have an  $\text{Mg}_2$  index of 0.24 mag (Golev & Prugniel 1998) corresponding to  $\text{Fe}/\text{H} = 1.1 Z_\odot$  (Terlevich et al. 1981). In addition, there appears to be no temperature gradient or evidence for cooling gas in the center of NGC 1291 to bias the metallicity determination of the gas. It appears that X-ray faint systems like NGC 1291 (and NGC 4697, although only a global metallicity was determined; SIB01) really do have low-metallicity gas even at their centers.

### 5.3. The Central Source

The presence of a bright, central X-ray point source is somewhat surprising considering there is little evidence in the literature that NGC 1291 hosts an AGN. While not as luminous as other low-luminosity AGNs, the spectral parameters of the central X-ray source are very similar to those found for a sample of low-luminosity AGNs, LINERs, and starbursts observed by *ROSAT* and *ASCA* by Ptak et al. (1999). Such spectral parameters are also common among narrow-line Seyfert 1 galaxies (Reeves & Turner 2000). It should be noted that in these systems the X-ray luminosity of the AGN is at least a factor of 10 higher than the AGN in NGC 1291. What is even more surprising is that the flux of the soft component was unchanged between OB1 and OB2, while the hard component decreased in intensity by a factor of 2 over the same time period. The excellent spatial resolution of *Chandra* confirms that the origin of the soft component lies within  $\sim 60$  pc from the central source and is almost assuredly associated with the central source.

This kind of temporal behavior in the soft and hard components has also been seen in the narrow-line Seyfert 1 galaxy Mrk 766 with *XMM-Newton* by Page et al. (2001). These authors find that the soft X-ray excess, as well as the ultraviolet emission observed with *XMM-Newton*'s Optical Monitor, varied very little throughout the observation, whereas the hard continuum component varied significantly. It is unlikely that the soft component can be reprocessed hard power-law emission, since in this case the fluxes

of the hard and soft components should vary together. It is possible that the soft emission emanates directly from the hot inner accretion disk (Malkan & Sargent 1982) and is the high-energy tail of the ultraviolet bump seen in these objects. Alternatively, the source of the soft X-ray emission may be the Compton up-scattering of the ultraviolet photons from this disk.

The detection of a low-luminosity active nucleus in NGC 1291 also explains the detection of unresolved 60 and 100  $\mu\text{m}$  emission in this galaxy (Rice et al. 1988). Bregman et al. (1995) point out that it was surprising that very little if any CO emission was detected in this galaxy given the 100  $\mu\text{m}$  flux of 10.7 Jy, based on the observed correlation of CO with 100  $\mu\text{m}$  emission in other galaxies. It is quite possible that the 100  $\mu\text{m}$  emission is associated with the AGN and not with dust associated with star formation in the bulge.

#### 5.4. Hot versus Cold Gas in Sa Galaxies

The ratio of hot to cold gas is a strong function of galaxy morphological type. The interstellar material in late-type spiral galaxies is predominantly atomic and molecular with trace amounts of hot gas, while in elliptical galaxies it is just the opposite, with S0 galaxies having a roughly equal mixture of the two (e.g., Bregman, Hogg, & Roberts 1992). As an Sa galaxy, we would expect NGC 1291 to have more cold than hot gas. This is indeed the case here, where the mass of the hot gas is  $5.8 \times 10^7 M_{\odot}$ , while the H I gas mass is  $1.3 \times 10^9 M_{\odot}$  (van Driel, Rots, & van Woerden 1988).

The H I distribution in NGC 1291, as is the case with several S0 and Sa galaxies, is ringlike in nature (van Driel et al. 1988). The central hole in the H I is 7 kpc in radius. An analysis of *ROSAT* PSPC data by Bregman et al. (1995) found that the X-ray emission appears to fill this hole. We confirm this result with our *Chandra* observations; hot, diffuse gas with a temperature of  $\sim 0.3$  keV is detected out to a radius of 5 kpc.

Whether the hot gas has actually displaced the cold gas or whether it is merely the case that cold gas is a disk phenomenon while hot gas is a bulge phenomenon is still an open question. As Bregman et al. (1995) point out, if the hot and cold gases are thermally coupled, convection and turbulent mixing can lead to the conversion of hot gas to cold gas and vice versa, causing the two phases to be spatially anticorrelated, with the phase with the higher column density winning out. A signature of this would be a softening of the spectrum of the hot gas with increasing radius, as successively more hot gas is cooled by the presence of cold gas. Indeed, there is a softening of the 0.7–1.0 keV/0.3–0.7 keV ratio with increasing radius (Fig. 7), although it should be noted that the softening occurs at a radius in which there is no detectable H I emission. A more definitive answer might be obtained with an Sa or S0 galaxy that does not have such a large hole in its H I distribution. Several galaxies in the H I sample of van Driel & van Woerden (1991) show complex H I morphology in the center of the galaxy. A high-resolution *Chandra* observation of the bulges of these galaxies might shed some light on the interaction (or lack of interaction) between the hot and cold phases of the ISM. If the two phases were thermally isolated, the cold gas would absorb soft X-rays from the hot gas behind it, leading to a hardening of the X-rays in the direction of the H I knots. Alternatively, if the phases are thermally coupled, we might expect the X-ray gas to fill the empty pockets in the H I distribu-

tion, indicating that cold gas has been turned into the hot phase in these regions.

## 6. CONCLUSIONS

Analyses of two *Chandra* observations of the bulge-dominated spiral NGC 1291 have revealed the primary X-ray-emitting components of the galaxy. The bulk of the X-rays (by counts and by luminosity) emanates from a collection of several dozen LMXBs that exhibit a range of spectral characteristics. A significantly smaller fraction of the X-ray emission comes from a 0.32 keV thermal gas with low metallicity. These observations demonstrate, along with *XMM-Newton* observations of the bulge of M31 (Shirey et al. 2001), that the X-ray emission of bulges of galaxies resemble that of a subclass of elliptical and S0 galaxies that are X-ray faint. The rather high temperatures measured for Sa galaxies with *Einstein* (Kim et al. 1992) were the result of the mixture of two spectrally distinct components, namely, LMXBs and hot gas.

The luminosity distribution function of LMXBs in the bulge of NGC 1291 can be compared to that of other early-type galaxies to explore differences in the LMXB populations from galaxy to galaxy. There are no LMXBs with luminosities greater than  $3 \times 10^{38}$  ergs  $\text{s}^{-1}$  in NGC 1291, where about seven were expected by scaling from NGC 4697 or NGC 1553. This lack of high-luminosity LMXBs is the cause of the wide spread in the stellar  $L_X/L_B$  values seen with previous X-ray instruments. Such a spread suggests that the production of LMXBs with massive primaries is not uniform from galaxy to galaxy, despite the uniformity of the present-day stellar population among early-type systems. On the other hand, below  $10^{38}$  ergs  $\text{s}^{-1}$  there is remarkable agreement in the LMXB functions of NGC 1291 and NGC 4697. This agreement is highly sensitive to the assumed distance of NGC 1291. If this agreement is a generic property of LMXBs in early-type systems, it can be used as an accurate distance indicator, one of the very few nonoptical methods for determining galactic distances.

The distribution of the hot gas can be described by the standard  $\beta$ -profile with  $r_{\text{core}} = 2.9$  and  $\beta = 0.45$ . The central density of the gas is  $0.28 \text{ cm}^{-3}$ , and the total mass of the gas is  $5.8 \times 10^7 M_{\odot}$ , far less than the mass of the H I in the galaxy. There is marginal evidence that the temperature and metallicity decrease slightly outside of 0.6 kpc. The temperature of the gas, while lower than in X-ray bright galaxies, is similar to that in other X-ray faint systems such as NGC 4697 and the bulge of M31 (SIB01; Shirey et al. 2001). The paucity of gas in the system is probably the result of the removal of most of the gas by supernova-driven winds rather than interaction with a cluster environment. The low measured metallicity of the gas is in conflict with the optically determined value of the metallicity of the bulge. The hot gas fills the hole in the H I distribution, possibly indicating that the hot gas has displaced the cold gas in the overlap region. However, future observations of Sa galaxies with smaller H I holes will be able to address this issue more conclusively.

Finally, the central point source is coincident with the optical center of the galaxy and exhibits significantly different spectral characteristics than the sum of the other resolved point sources. Above 1.5 keV, the spectrum is adequately described by a highly absorbed ( $N_{\text{H}} > 10^{22} \text{ cm}^{-2}$ ) power law with  $\Gamma = 1.9$  and the luminosity varied by

a factor of 2 between the two observations. Below 1.5 keV, there is an excess of soft photons over what is expected from hot gas within the extraction region. The soft component is of equal strength in the two observations, can be modeled by a MEKAL model with a temperature of 0.75 keV and low metallicity, and has a luminosity that is 5%–10% that of the hard component. The parameters of both the hard and soft components are very similar to those of low-luminosity AGNs studied previously with *ASCA* and *ROSAT* (Ptak et al. 1999).

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