

## CHANDRA X-RAY OBSERVATIONS OF THE SPIRAL GALAXY M81

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### ABSTRACT

A *Chandra X-Ray Observatory* ACIS-S imaging observation is used to study the population of X-ray sources in the nearby Sab galaxy M81 (NGC 3031). A total of 177 sources are detected with 124 located within the  $D_{25}$  isophote to a limiting X-ray luminosity of  $\sim 3 \times 10^{36}$  ergs s<sup>-1</sup>. Source positions, count rates, luminosities in the 0.3–8.0 keV band, limiting optical magnitudes, and potential counterpart identifications are tabulated. Spectral and timing analysis of the 36 brightest sources are reported including the low-luminosity active galactic nucleus, SN 1993J, and the *Einstein*-discovered ultraluminous X-ray source X6. The nucleus accounts for  $\sim 86\%$ , or  $5 \times 10^{40}$  ergs s<sup>-1</sup>, of the total X-ray emission from M81. Its spectrum is well fitted by an absorbed power law with photon index  $1.98 \pm 0.08$ , consistent with previous observations (average index 1.9). SN 1993J has softened and faded since its discovery. At an age of 2594 days, SN 1993J displayed a complex thermal spectrum from a reverse shock rich in Fe L and highly ionized Mg, Si, and S but lacking O. A hard X-ray component, emitted by a forward shock, is also present. X6 is spatially coincident with a stellar object with optical brightness and colors consistent with an O9–B1 main-sequence star. It is also coincident with a weak radio source with a flux density of  $\sim 95$   $\mu$ Jy at  $\lambda = 3.6$  cm. The continuum-dominated X-ray spectrum of X6 is most closely reproduced by a blackbody disk model suggesting the X-ray source is an  $\sim 18 M_{\odot}$  object accreting at nearly its Eddington limit.

The non-nuclear point source population of M81 accounts for 88% of the non-nuclear X-ray luminosity of  $8.1 \times 10^{39}$  ergs s<sup>-1</sup>. The remaining (unresolved) X-ray emission is confined within  $\sim 2$  kpc of the galactic center. The spatial distribution of this emission and of the resolved X-ray bulge sources closely follows that of the bulge optical light. In particular, there is no evidence for an X-ray signature accompanying the filamentary H $\alpha$  or excess UV emission seen in the central  $\lesssim 1.0$  kpc of the galaxy. The shape of the luminosity function of the bulge sources is a power law with a break at  $\sim 4 \times 10^{37}$  ergs s<sup>-1</sup>; suggesting the presence of an aging ( $\sim 400$  Myr) population of low-mass X-ray binaries. Extrapolating this luminosity function to lower luminosities accounts for only  $\sim 10\%$  of the unresolved X-ray emission. Spectroscopically, the unresolved emission can be represented as a combination of soft,  $kT \sim 0.3$  keV, optically thin plasma emission and of a  $\Gamma = 1.6$  power law. The unresolved bulge X-ray emission is therefore most likely a combination of hot gas and of one or more large and distinct populations of low-luminosity X-ray sources confined in the gravitational potential and tracing the old population of bulge stars. The distribution of disk sources shows a remarkably strong correlation with spiral arms with the brightest disk sources located closest to spiral arms. The luminosity function of sources near the spiral arms is a pure power law (slope  $-0.48 \pm 0.03$ ), while that of sources further away exhibits a break or cutoff in the power-law distribution with no high-luminosity members. This is interpreted as a natural consequence of the passage of spiral density waves that leave the brightest (when averaged over their lifetimes) and shortest-lived X-ray sources immediately downstream of the spiral arms. Consistent with model predictions, we conclude that the shapes of the X-ray luminosity functions of the different galactic components of M81 are most likely governed by the birth rates and lifespans of their constituent X-ray source populations and that the luminosity functions can be used as a measure of the star formation histories of their environments.

*Subject headings:* galaxies: individual (M81) — supernovae: individual (SN 1993J) — X-rays: binaries —  
X-rays: galaxies — X-rays: stars

*On-line material:* machine-readable table

### 1. INTRODUCTION

Systematic investigations of the X-ray properties of normal galaxies began in earnest with the *Einstein* observatory over two decades ago. The picture that emerged for spiral galaxies (see the early reviews by Long & van Speybroeck

1983, Helfand 1984, and Fabbiano 1989) is that the bulk of the X-ray emission takes place in two distinct physical environments: the star-forming disks of late-type spiral and irregular galaxies and among the old stellar population in dense globular clusters and compact bulges at the centers of early-type spiral galaxies. In addition to these trends along the Hubble sequence, variations were sometimes found among spiral galaxies of similar morphological type suggesting a dependence on star formation histories. In particular, the brightest X-ray emissions are associated with starbursts in merging and interacting galaxies (David, Jones, & Forman 1992). Thus, by tracing the endpoints of stellar evolution, the X-ray source populations of external

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galaxies provide important clues to the physical nature and evolutionary history of their hosts.

The contemporary view for spiral galaxies is rapidly being refined following the launch of the *Chandra* and *XMM-Newton* X-ray Observatories. Moderately deep images reveal point sources to limiting X-ray luminosities of order  $10^{37}$  ergs  $s^{-1}$  in galaxies out to Virgo cluster distances. While this samples only the high-luminosity end of the distribution of X-ray sources, of order 100 sources are routinely detected in normal galaxies similar to our own. Reliable spectral analysis is usually limited to an even smaller subset of the brightest individual sources. Nevertheless, using probabilistic methods, the observed sample of X-ray sources can help us understand current-epoch galaxy evolution in its broader context.

A formal expression of the relationship between the star formation history of local galaxies and their observed X-ray source populations has recently been put forth by Wu (2001; see also Wu et al. 2003a, 2003b; Kilgard et al. 2002; Dalton & Sarazin 1995). There it was shown that the basic shape of the observed X-ray luminosity function is governed simply by the birth and death rates of the source population under the assumption that the more luminous X-ray sources are shorter-lived. Thus, in the absence of ongoing star formation, the luminosity function will develop a cutoff at high luminosity that evolves toward lower luminosity. Conversely, if the population of X-ray sources is replenished through star formation processes, such as is found in spiral arms, then a power-law-shaped luminosity function can be sustained.

Certain complications arise when applying this basic interpretation to X-ray populations in individual galaxies (Wu et al. 2003a, 2003b). Among these are the presence of different classes of X-ray sources, such as supernova remnants and accreting compact objects, which evolve on differing timescales; alternative source-formation mechanisms uncorrelated with stellar evolution such as binary captures in globular clusters; and nonsteady or luminosity-limited emission characteristics such as those associated with X-ray transients and novae and in Eddington-limited neutron star binaries, respectively. Therefore, only when specific counterparts to individual X-ray sources are identified and their multiwavelength properties assessed can the full power of the hypothesis of Wu et al. (2003a, 2003b) be applied to address the nature and evolution of X-ray sources in different environments.

The nearby Sab galaxy M81 (NGC 3031) is ideal for such a study in that it contains both a strong two-arm grand-design spiral pattern and a well-defined circumnuclear bulge. The distance to M81, 3.6 Mpc, has been well established from Cepheid measurements (Freedman et al. 1994) which are in good agreement with other distance estimates (Ferrarese et al. 2000). Populations of several classes of objects in M81 have been investigated and cataloged including globular clusters (Perelmuter & Racine 1995; Chandar, Ford, & Tsvetanov 2001), supernova remnants (Matonick & Fesen 1997), H II regions (Hodge & Kennicutt 1983; Petit, Sivan, & Karachentsev 1988), and stars and star clusters (Zickgraf & Humphreys 1991; Ivanova 1992; Sholukhova et al. 1998). In addition, the plane of the galaxy is oriented  $32^\circ$  from face-on allowing detailed mapping of the velocity field (Goat 1976; Rots & Shane 1975; Adler & Westphal 1996) for dynamical studies and testing spiral density wave models (Visser 1980; Roberts & Hausman 1984).

The center of M81 contains a compact radio core (Bartel et al. 1982) surrounded by a region of enhanced far-infrared (Rice 1993; Davidge & Courteau 1999), H $\alpha$  (Devereux, Jacoby, & Ciardullo 1995), and ultraviolet (Hill et al. 1992; Reichen et al. 1994) emission extending to  $\sim 50''$  ( $\sim 900$  pc). This emission probably comes from an old population of hot, low-mass stars rather than from young massive stars (O'Connell et al. 1992; Devereux, Ford, & Jacoby 1997).

In contrast to the bulge, H I velocity contours show a sharp discontinuity beyond the bulge identified as a spiral velocity shock (Visser 1980). Downstream of this shock are regions of star formation in the spiral arms. The distributions of these components are consistent (Kaufman et al. 1989) with density wave models predicting a broad spiral density enhancement (e.g., Roberts & Hausman 1984).

Beyond the visible disk of M81 is an envelope of neutral hydrogen (Roberts 1972) enclosing M81 and nearby group members. A bridge of gas, a relic of tidal interaction (Cottrell 1977), connects M81 and the starburst galaxy M82.

The hypothesis of Wu (2001) and Wu et al. (2003a, 2003b) was motivated in large part by the initial results from our *Chandra* observation of M81 presented in Tennant et al. (2001). There it was shown that the X-ray luminosity function of the population of bulge sources displays a break at  $\sim 4 \times 10^{37}$  ergs  $s^{-1}$  similar to that observed in M31 (e.g., Shirey et al. 2001). The X-ray luminosity function of the disk sources, on the other hand, follows a single power-law slope over three decades in flux. This is what is expected if an impulsive episode of star formation occurred in the bulge in the past, ostensibly during an encounter between M81 and one of its companion galaxies, while continuous star formation in the disk is being driven by the passage of spiral density waves.

Here we build upon the earlier work of Tennant et al. (2001). After presenting detailed information on the individual X-ray sources in § 3 and in-depth analysis of the brightest objects in § 4, the properties of the bulge (§ 5) and disk (§ 6) regions are addressed separately then discussed (§ 7) within the common framework of galaxy evolution.

## 2. OBSERVATIONS

The primary X-ray data set is a 49926 s observation of M81 obtained on 2000 May 7 with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS) spectroscopy array operating in imaging mode. Unless otherwise noted, references to X-ray data will refer to this data set. The X-ray data were reprocessed by the *Chandra* X-ray Center (CXC) on 2001 January 4. This reprocessed data are used in this work. There are no significant differences between the reprocessed data and the originally distributed data analyzed by Tennant et al. (2001). The observation was taken in faint timed exposure mode at 3.241 s frame $^{-1}$  at a focal plane temperature of  $-120^\circ\text{C}$ . Standard CXC processing has applied aspect corrections and compensated for spacecraft dither.

The primary target, SN 1993J, was located near the nominal aimpoint on the back-illuminated (BI) device S3. The nucleus of M81 lies  $2'.79$  from SN 1993J toward the center of S3 in this observation. Accurate positions of these two objects and two G0 stars located on device S2 were used to identify any offset and to determine absolute locations of the remaining *Chandra* sources as well as objects in other X-ray images and those obtained at other wavelengths. Table 1 shows that the positions are accurate to within  $1''.4$ .

TABLE 1  
M81 ASTROMETRY

OBJECT	<i>Chandra</i> POSITION		CATALOGED POSITION	
	R.A.	Decl.	R.A.	Decl.
SN 1993J.....	9 55 24.77	69 1 13.4	9 55 24.77	69 1 13.7 (1)
Nucleus.....	9 55 33.19	69 3 55.1	9 55 33.17	69 3 55.1 (2)
PPM 17242 .....	9 55 1.00	68 56 22.1	9 55 1.00	68 56 22.2 (3)
PPM 17243 .....	9 55 2.57	68 56 21.2	9 55 2.76	68 56 22.1 (3)

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

REFERENCES.—(1) Marcaide et al. 1993; (2) Ma et al. 1998; (3) Positions and Proper Motions Catalog.

No offset correction was applied to the *Chandra* X-ray positions.

A charge transfer inefficiency (CTI) corrector algorithm (Townsend et al. 2000) was then applied to the Level 1 event list to partially correct for the charge loss and charge smearing effects of CTI in the ACIS detectors. Matching response matrices were also provided by L. Townsend. After correction, a single response matrix is adequate for sources on the S3 device since the spectral resolution does not exhibit a strong spatial dependence. This is particularly advantageous for analysis of the unresolved emission extending over the  $\sim 8'$  diameter bulge of M81, which is located entirely within the S3 device.

The corrector algorithm was applied to all but the front-illuminated (FI) device S4 because no correction was available for that device. Instead, the Level 2 event list was used and the DESTREAK algorithm<sup>5</sup> was applied to remove charge randomly deposited along pixel rows during read out.

The entire data set was then cleaned of bad pixels and columns and the standard grade set and events in pulse invariant (PI) channels corresponding to  $\sim 0.2$  to 8.0 keV were selected for source detection. The range 0.3 to 8.0 keV is used for spectral analysis.

No periods of high particle background occurred during the observation. The 0.3–8.0 keV background in the BI device S3 is  $\sim 0.04$  counts pixel<sup>-1</sup>, and that in the FI devices is  $\sim 0.01$  counts pixel<sup>-1</sup> for the observation. Separate background spectra were extracted from large source-free regions of each device. The background spectrum for S3 was chosen far from the nucleus because excess X-ray emission was detected near the nucleus (§ 5). The background spectra appear similar to deep quiescent blank sky compilations available from the CXC.

The detector viewing area covers 57% of the optical extent of the galaxy, defined as the ellipse of major diameter 26.9 corresponding to the  $D_{25}$  isophote as tabulated in de Vaucouleurs et al. (1991), oriented at position angle 149°, and with major-to-minor axis ratio 1.94:1 corresponding to the 58° inclination angle of M81. This area includes all of the S3 device, approximately half of each of the S2 and S4 devices, and the outer corner of I3. The data from each device are analyzed independently owing to differing energy resolutions, low-energy responses, and background signals.

In addition to this primary data set, a 2.4 ks ACIS-S image taken 2000 March 21 and numerous *ROSAT* PSPC and HRI data sets were used to construct long-term light curves of the brightest sources (see Immler & Wang 2001 for their analysis of the *ROSAT* observations).

### 3. THE DISCRETE X-RAY SOURCE POPULATION

Table 2 lists the 177 discrete X-ray sources detected in the primary *Chandra* observation. The table lists the source positions (in order of increasing right ascension), the aperture-corrected number of source counts, the signal-to-noise ratio for the count rate, apparent visual magnitudes derived from either *Hubble Space Telescope* (HST) WFPC2 images or from the Perlmutter & Racine (1995) catalog of bright objects, ACIS CCD device identification, global environment (where “b” denotes bulge, “d” denotes disk, and  $D_{25}$  denotes source is outside the  $D_{25}$  isophote), and the unabsorbed luminosity in the 0.3–8.0 keV energy range. The table also lists corresponding X-ray detections from *Einstein* (denoted “X,” Fabbiano 1988) and *ROSAT* (“P” and “H” denoting PSPC- and HRI-identified sources, respectively, Immler & Wang 2001), and potential source type based on spatial correlations with cataloged objects or on other information. Explanations of the quantitative entries are given in the following subsections. References to *Chandra* X-ray source numbers in this work refer to the source numbering adopted for Table 2.

#### 3.1. X-Ray Source Detection

A source-finding method was used that assumes a source is located at a given position and compares the distribution of detected events to a known point spread function (PSF). The algorithm first calculates the fraction of the PSF within each pixel within a detection region. Then, using the PSF fraction as the independent variable, it calculates an unweighted least-squares fit of a straight line to the counts detected in the pixels in the region. If a source is present, then the slope of the line will be positive and will represent the total number of counts from the source (integrated over the PSF). The line intercept is the background per pixel. A key value is the uncertainty in the slope and hence the number of source counts. The uncertainty is determined by applying the standard propagation of errors directly to the sums.

The algorithm then calculates the estimated source counts (slope) and error at every pixel in the image. The estimated source counts divided by the uncertainty is the signal-to-noise ratio (S/N). If the S/N exceeds some threshold, then there is a source in the neighborhood. However, since both source counts and error increase near a source, the S/N is not as sharply peaked as either component individually. To best separate sources in confused regions, a source is defined to be a peak in the estimated source count spatial distribution and must also exceed a minimum S/N threshold. The threshold S/N is best defined by constructing the S/N histogram. This histogram is roughly a Gaussian core centered near zero (due to noise) with exponential wings (due to sources). By fitting the core to a Gaussian, the S/N value for which the Gaussian will contribute less than one source in the field can be estimated. This threshold is as low as 2.5 for a source on axis and as high as 3.0 for a source far off-axis. For this paper a constant value of 2.8 is used as the

<sup>5</sup> See <http://asc.harvard.edu/ciao2.1/downloads/scripts/destreak.ps>.

TABLE 2  
M81 DISCRETE X-RAY SOURCES

Number (1)	R.A. (J2000) (2)	Decl. (J2000) (3)	Count Rate ( $10^{-4} \text{ s}^{-1}$ ) (4)	S/N (5)	$m_V$ (6)	CCD (7)	Region (8)	$L_X$ ( $10^{37} \text{ ergs s}^{-1}$ ) (9)	Comment (10)
1.....	9 52 38.50	68 56 37.5	24.05 ± 2.19	7.45	...	i2	$D_{25}$	4.40 ± 0.40	
2.....	9 52 39.86	69 03 59.8	12.73 ± 1.59	4.82	>16.52	i3	$D_{25}$	2.33 ± 0.29	P1
3.....	9 52 41.52	68 55 26.6	18.07 ± 1.90	6.10	...	i2	$D_{25}$	3.31 ± 0.35	
4.....	9 52 49.86	68 59 25.3	12.75 ± 1.59	5.18	...	i2	$D_{25}$	2.33 ± 0.29	P4
5.....	9 52 59.76	69 07 43.1	15.90 ± 1.78	6.49	...	i3	$D_{25}$	2.91 ± 0.33	P5
6.....	9 53 02.06	69 09 38.8	10.82 ± 1.47	4.53	>21.02	i3	$D_{25}$	1.98 ± 0.27	
7.....	9 53 04.08	69 01 43.7	10.00 ± 1.41	4.12	...	i2	$D_{25}$	1.83 ± 0.26	
8.....	9 53 10.54	69 00 02.8	7.44 ± 1.22	4.13	>16.72	i2	$D_{25}$	1.36 ± 0.22	H2, P6, Gal?
9.....	9 53 16.05	69 00 03.4	6.69 ± 1.15	3.73	...	i2	$D_{25}$	1.22 ± 0.21	
10.....	9 53 17.96	69 06 43.2	14.36 ± 1.69	5.89	>20.83	i3	$D_{25}$	2.63 ± 0.31	H3, P7
11.....	9 53 18.71	69 02 19.1	6.19 ± 1.11	3.81	...	i2	$D_{25}$	1.13 ± 0.20	
12.....	9 53 19.37	69 10 45.1	7.27 ± 1.20	3.28	...	i3	$D_{25}$	1.33 ± 0.22	
13.....	9 53 27.53	69 04 19.3	16.56 ± 1.81	6.95	...	i3	$D_{25}$	3.03 ± 0.33	P8
14.....	9 53 32.65	69 02 20.3	5.29 ± 1.03	3.53	...	i2	$D_{25}$	0.97 ± 0.19	
15.....	9 53 33.32	69 03 42.0	7.56 ± 1.23	4.33	...	i3	$D_{25}$	1.38 ± 0.22	
16.....	9 53 33.87	68 58 20.7	12.42 ± 1.57	6.35	18.65	i2	$D_{25}$	2.27 ± 0.29	P9, Extended?
17.....	9 53 36.05	69 05 45.4	5.71 ± 1.07	3.61	...	i3	$D_{25}$	1.05 ± 0.20	
18.....	9 53 37.69	68 59 19.1	16.57 ± 1.82	7.24	...	i2	$D_{25}$	3.03 ± 0.33	
19.....	9 53 42.03	68 59 17.9	10.33 ± 1.43	5.61	>21.11	i2	$D_{25}$	1.89 ± 0.26	P11
20.....	9 53 44.48	69 05 26.5	2.98 ± 0.77	2.98	...	i3	$D_{25}$	0.55 ± 0.14	
21.....	9 53 48.61	69 00 21.0	2.85 ± 0.75	2.93	...	i2	$D_{25}$	0.52 ± 0.14	
22.....	9 53 50.85	69 05 26.5	4.07 ± 0.90	3.09	...	i3	$D_{25}$	0.75 ± 0.16	
23.....	9 53 51.59	68 55 37.4	4.82 ± 0.98	3.47	...	i2	$D_{25}$	0.88 ± 0.18	
24.....	9 53 51.88	69 02 49.9	19.14 ± 1.95	8.06	...	i3	$D_{25}$	3.50 ± 0.36	H5, P14
25.....	9 53 53.41	69 03 59.4	4.48 ± 0.94	3.36	...	i3	$D_{25}$	0.82 ± 0.17	
26.....	9 53 53.67	69 03 18.0	3.24 ± 0.80	2.87	...	i3	$D_{25}$	0.59 ± 0.15	
27.....	9 53 57.47	69 03 53.8	16.92 ± 1.83	7.49	...	i3	$D_{25}$	3.10 ± 0.34	H6, P15
28.....	9 54 02.15	69 01 26.7	3.47 ± 0.83	3.02	...	i2	$D_{25}$	0.64 ± 0.15	
29.....	9 54 06.73	69 08 41.7	11.37 ± 1.50	5.95	...	i3	d	2.08 ± 0.28	
30.....	9 54 14.00	69 05 37.9	12.96 ± 1.61	6.71	...	i3	d	2.37 ± 0.29	
31.....	9 54 14.92	69 06 12.1	2.75 ± 0.74	2.84	...	i3	d	0.50 ± 0.14	
32.....	9 54 21.30	68 44 41.6	17.03 ± 1.84	4.19	...	s1	$D_{25}$	2.32 ± 0.25	
33.....	9 54 25.49	68 46 51.7	29.01 ± 2.40	6.75	...	s1	$D_{25}$	3.94 ± 0.33	
34.....	9 54 26.42	68 43 43.5	18.67 ± 1.93	3.14	...	s1	$D_{25}$	2.54 ± 0.26	
35.....	9 54 27.84	68 53 11.3	3.44 ± 0.83	3.07	...	s2	$D_{25}$	0.63 ± 0.15	
36.....	9 54 32.66	68 47 44.1	26.95 ± 2.31	5.77	...	s1	$D_{25}$	3.66 ± 0.31	
37.....	9 54 33.16	68 52 29.0	27.96 ± 2.36	9.51	...	s2	$D_{25}$	6.30 ± 1.10	P18
38.....	9 54 38.67	68 52 42.9	8.18 ± 1.28	4.90	...	s2	$D_{25}$	1.50 ± 0.23	
39.....	9 54 39.23	68 45 49.4	73.05 ± 3.81	12.55	...	s1	$D_{25}$	9.93 ± 0.52	
40.....	9 54 41.82	68 56 47.6	11.91 ± 1.54	6.51	...	s2	$D_{25}$	2.18 ± 0.28	
41.....	9 54 41.99	69 02 43.7	11.05 ± 1.48	6.38	>HST	s3	d	1.50 ± 0.20	P21
42.....	9 54 44.34	68 56 11.0	5.61 ± 1.06	4.44	>19.81	s2	$D_{25}$	1.03 ± 0.19	
43.....	9 54 45.30	68 56 58.6	58.15 ± 3.40	14.30	>13.81	s2	$D_{25}$	10.64 ± 0.62	H8, P22, *
44.....	9 54 46.79	69 05 12.6	3.58 ± 0.84	3.07	23.01	s3	d	0.49 ± 0.11	
45.....	9 54 47.18	69 01 01.4	4.64 ± 0.96	3.77	...	s3	d	0.63 ± 0.13	
46.....	9 54 51.49	68 51 43.5	9.50 ± 1.37	5.31	...	s2	$D_{25}$	1.74 ± 0.25	
47.....	9 54 53.96	68 54 55.0	6.40 ± 1.13	4.62	...	s2	$D_{25}$	1.17 ± 0.21	
48.....	9 54 55.15	69 04 20.3	2.99 ± 0.77	3.40	...	s3	d	0.41 ± 0.10	
49.....	9 54 55.60	68 51 59.6	4.15 ± 0.91	2.85	...	s2	$D_{25}$	0.76 ± 0.17	
50.....	9 54 56.05	69 05 17.4	3.43 ± 0.83	3.18	23.79	s3	d	0.47 ± 0.11	
51.....	9 54 57.59	69 02 41.1	32.91 ± 2.56	10.82	...	s3	d	5.00 ± 0.60	
52.....	9 55 00.11	69 07 45.2	189.55 ± 6.14	25.64	22.7(I)	s3	d	27.00 ± 0.60	X10, H10, P25
53.....	9 55 00.28	69 04 36.9	2.61 ± 0.72	2.86	...	s3	d	0.36 ± 0.10	
54.....	9 55 00.36	69 01 48.9	2.80 ± 0.75	2.90	...	s3	d	0.38 ± 0.10	
55.....	9 55 00.48	68 56 32.8	2.42 ± 0.69	2.91	...	s2	d	0.44 ± 0.13	
56.....	9 55 01.00	68 56 22.1	10.48 ± 1.44	6.11	...	s2	$D_{25}$	1.92 ± 0.26	*
57.....	9 55 01.05	69 07 27.1	55.15 ± 3.31	13.88	...	s3	d	22.00 ± 2.80	
58.....	9 55 01.40	68 53 29.7	13.66 ± 1.65	6.50	...	s2	$D_{25}$	2.50 ± 0.30	
59.....	9 55 01.65	69 10 42.3	9.00 ± 1.34	5.03	...	s4	d	1.65 ± 0.24	P26
60.....	9 55 02.57	68 56 21.2	12.73 ± 1.59	6.78	...	s2	$D_{25}$	2.33 ± 0.29	H11, P27, *
61.....	9 55 05.43	68 44 22.8	85.31 ± 4.12	12.94	...	s1	$D_{25}$	11.60 ± 0.56	
62.....	9 55 05.62	68 58 52.1	3.60 ± 0.85	3.11	...	s2	d	0.66 ± 0.15	P28, H II
63.....	9 55 06.34	69 04 05.7	10.52 ± 1.45	5.79	...	s3	d	1.43 ± 0.20	

TABLE 2—Continued

Number (1)	R.A. (J2000) (2)	Decl. (J2000) (3)	Count Rate ( $10^{-4} \text{ s}^{-1}$ ) (4)	S/N (5)	$m_V$ (6)	CCD (7)	Region (8)	$L_X$ ( $10^{37} \text{ ergs s}^{-1}$ ) (9)	Comment (10)
64.....	9 55 08.91	68 57 22.9	$2.89 \pm 0.76$	3.03	>19.69	s2	d	$0.53 \pm 0.14$	
65.....	9 55 09.28	68 53 35.6	$10.34 \pm 1.43$	5.94	...	s2	$D_{25}$	$1.89 \pm 0.26$	
66.....	9 55 09.66	69 07 43.4	$21.26 \pm 2.06$	8.43	23.19	s3	d	$2.89 \pm 0.28$	H II
67.....	9 55 09.77	69 04 07.8	$18.93 \pm 1.94$	8.29	>17.29	s3	b	$3.50 \pm 0.70$	X2, H13, P29, GC?
68.....	9 55 09.80	69 08 35.4	$5.57 \pm 1.05$	2.97	21.45	s4	d	$1.02 \pm 0.19$	
69.....	9 55 10.29	69 05 02.4	$201.59 \pm 6.33$	27.36	22.79	s3	b	$26.70 \pm 1.00$	X3, H14, P31
70.....	9 55 10.71	69 08 43.7	$13.25 \pm 1.62$	6.23	22.86	s4	d	$2.42 \pm 0.30$	P30, SNR
71.....	9 55 11.81	68 57 47.9	$2.92 \pm 0.76$	2.91	...	s2	d	$0.53 \pm 0.14$	
72.....	9 55 12.44	69 01 21.5	$2.53 \pm 0.71$	2.83	>HST	s3	d	$0.34 \pm 0.10$	
73.....	9 55 14.12	69 12 36.1	$12.74 \pm 1.59$	5.56	...	s4	d	$2.33 \pm 0.29$	P32
74.....	9 55 14.61	69 06 40.4	$3.94 \pm 0.89$	3.37	24.03	s3	b	$0.54 \pm 0.12$	
75.....	9 55 15.22	69 05 38.0	$7.40 \pm 1.21$	4.83	24.36	s3	b	$1.01 \pm 0.16$	
76.....	9 55 15.56	68 54 27.5	$4.70 \pm 0.97$	4.18	...	s2	d	$0.86 \pm 0.18$	
77.....	9 55 15.99	68 51 59.6	$9.70 \pm 1.39$	5.38	...	s2	$D_{25}$	$1.77 \pm 0.25$	
78.....	9 55 19.76	69 07 33.7	$6.08 \pm 1.10$	3.90	22.05	s3	d	$0.83 \pm 0.15$	H II, SNR
79.....	9 55 19.95	69 03 52.0	$2.43 \pm 0.70$	2.99	>HST	s3	b	$0.33 \pm 0.09$	Radio
80.....	9 55 21.85	69 03 44.9	$3.52 \pm 0.84$	3.34	>HST	s3	b	$0.48 \pm 0.11$	
81.....	9 55 21.87	69 05 22.3	$37.95 \pm 2.75$	11.53	>HST	s3	b	$4.80 \pm 0.50$	
82.....	9 55 21.99	69 06 37.6	$35.61 \pm 2.66$	11.08	17.14	s3	b	$5.10 \pm 1.10$	H16, P33, GC?
83.....	9 55 22.16	69 05 10.6	$178.55 \pm 5.96$	25.84	>HST	s3	b	$22.00 \pm 0.90$	H15, P34
84.....	9 55 23.71	68 58 48.9	$3.61 \pm 0.85$	3.85	...	s2	d	$0.66 \pm 0.16$	
85.....	9 55 24.30	69 04 39.3	$6.06 \pm 1.10$	4.46	>HST	s3	b	$0.82 \pm 0.15$	
86.....	9 55 24.36	69 09 57.9	$155.20 \pm 5.55$	23.19	...	s4	d	$35.00 \pm 3.00$	X4, H17, P35
87.....	9 55 24.41	69 14 50.7	$12.24 \pm 1.56$	4.80	>15.82	s4	d	$2.24 \pm 0.29$	
88.....	9 55 24.77	69 01 13.4	$596.32 \pm 10.89$	46.98	>20.22	s3	d	$48.00 \pm 2.00$	SN 1993J, H18, P36
89.....	9 55 26.31	69 04 37.3	$12.55 \pm 1.58$	6.52	>HST	s3	b	$1.71 \pm 0.21$	
90.....	9 55 26.57	69 04 00.4	$3.82 \pm 0.87$	2.83	>HST	s3	b	$0.52 \pm 0.12$	
91.....	9 55 26.93	69 05 42.4	$6.29 \pm 1.12$	4.18	...	s3	b	$0.86 \pm 0.15$	
92.....	9 55 27.01	69 04 15.3	$16.24 \pm 1.80$	7.45	>HST	s3	b	$2.21 \pm 0.24$	
93.....	9 55 27.28	69 02 48.0	$28.07 \pm 2.36$	9.77	>27.76	s3	b	$3.70 \pm 0.50$	
94.....	9 55 27.85	68 49 52.9	$10.25 \pm 1.43$	4.05	...	s1	$D_{25}$	$1.39 \pm 0.19$	
95.....	9 55 28.03	69 04 07.9	$38.02 \pm 2.75$	11.48	>HST	s3	b	$5.70 \pm 0.60$	
96.....	9 55 28.44	69 02 44.5	$12.02 \pm 1.55$	6.04	>HST	s3	b	$1.64 \pm 0.21$	SSS
97.....	9 55 28.82	69 06 12.9	$11.87 \pm 1.54$	6.17	...	s3	b	$1.61 \pm 0.21$	H20
98.....	9 55 29.20	69 03 21.1	$4.85 \pm 0.98$	4.11	>HST	s3	b	$0.66 \pm 0.13$	
99.....	9 55 29.28	69 15 57.2	$9.92 \pm 1.40$	3.21	...	s4	$D_{25}$	$1.82 \pm 0.26$	H19
100.....	9 55 30.21	69 03 18.4	$12.64 \pm 1.59$	6.47	>HST	s3	b	$1.72 \pm 0.22$	
101.....	9 55 30.25	69 02 46.8	$6.55 \pm 1.14$	4.48	>HST	s3	b	$0.89 \pm 0.16$	
102.....	9 55 31.38	69 04 19.5	$46.44 \pm 3.04$	12.62	>HST	s3	b	$6.80 \pm 0.60$	
103.....	9 55 32.61	69 05 13.0	$2.99 \pm 0.77$	2.85	>HST	s3	b	$0.41 \pm 0.10$	
104.....	9 55 32.66	69 02 31.4	$3.22 \pm 0.80$	2.95	22.87	s3	b	$0.44 \pm 0.11$	
105.....	9 55 32.99	69 00 33.3	$1614 \pm 18$	73.39	24.13	s3	d	$270 \pm 10$	X6, H21, P37
106.....	9 55 33.17	69 03 55.1	$5964 \pm 34$	140.0	15.42	s3	b	$3400 \pm 233$	X5, H22, P38
107.....	9 55 33.92	69 03 43.3	$13.92 \pm 1.66$	6.21	>HST	s3	b	$1.89 \pm 0.23$	
108.....	9 55 34.12	69 07 13.1	$7.75 \pm 1.24$	4.73	...	s3	d	$1.05 \pm 0.17$	
109.....	9 55 34.32	69 03 50.9	$45.90 \pm 3.02$	9.31	>HST	s3	b	$4.20 \pm 0.40$	
110.....	9 55 34.56	69 03 39.0	$8.64 \pm 1.31$	4.35	19.52	s3	b	$1.18 \pm 0.18$	
111.....	9 55 34.62	69 02 50.0	$16.79 \pm 1.83$	7.58	>HST	s3	b	$2.28 \pm 0.25$	
112.....	9 55 34.65	69 03 51.4	$52.38 \pm 3.23$	8.47	22.73	s3	b	$5.80 \pm 0.60$	
113.....	9 55 34.71	69 04 53.9	$38.03 \pm 2.75$	11.84	>HST	s3	b	$4.30 \pm 0.50$	
114.....	9 55 34.81	69 03 13.5	$16.21 \pm 1.79$	7.23	20.78	s3	b	$2.20 \pm 0.24$	
115.....	9 55 34.90	69 04 07.9	$19.51 \pm 1.97$	7.17	>HST	s3	b	$3.10 \pm 0.50$	
116.....	9 55 34.98	69 03 42.3	$118.14 \pm 4.85$	20.38	>HST	s3	b	$19.50 \pm 1.00$	
117.....	9 55 35.28	68 55 10.6	$31.02 \pm 2.48$	10.59	...	s2	d	$6.00 \pm 1.00$	H24
118.....	9 55 35.29	69 03 15.9	$56.97 \pm 3.37$	13.90	>HST	s3	b	$7.40 \pm 0.50$	H23
119.....	9 55 35.40	69 05 57.7	$4.55 \pm 0.95$	3.64	...	s3	b	$0.62 \pm 0.13$	
120.....	9 55 35.56	69 03 54.3	$46.87 \pm 3.05$	10.55	>HST	s3	b	$3.60 \pm 0.60$	
121.....	9 55 35.72	69 06 37.7	$7.65 \pm 1.23$	3.86	>20.66	s3	d	$1.04 \pm 0.17$	
122.....	9 55 36.29	69 02 44.8	$13.49 \pm 1.64$	6.76	>HST	s3	b	$1.83 \pm 0.22$	
123.....	9 55 36.45	69 02 40.5	$7.69 \pm 1.24$	4.67	>HST	s3	b	$1.05 \pm 0.17$	
124.....	9 55 36.75	69 06 33.2	$13.82 \pm 1.66$	6.90	>19.83	s3	d	$1.88 \pm 0.23$	H II, SNR
125.....	9 55 36.87	68 56 56.2	$3.03 \pm 0.78$	3.40	...	s2	d	$0.55 \pm 0.14$	
126.....	9 55 37.05	69 04 33.3	$28.54 \pm 2.38$	10.34	>HST	s3	b	$6.40 \pm 1.00$	
127.....	9 55 37.28	69 02 07.3	$3.50 \pm 0.83$	3.11	18.41	s3	b	$0.48 \pm 0.11$	GC?

TABLE 2—*Continued*

Number (1)	R.A. (J2000) (2)	Decl. (J2000) (3)	Count Rate ( $10^{-4} \text{ s}^{-1}$ ) (4)	S/N (5)	$m_V$ (6)	CCD (7)	Region (8)	$L_X$ ( $10^{37} \text{ ergs s}^{-1}$ ) (9)	Comment (10)
128.....	9 55 37.60	69 04 57.7	10.60 ± 1.45	6.08	23.10	s3	b	1.44 ± 0.20	
129.....	9 55 37.66	69 03 16.2	9.06 ± 1.34	5.43	>HST	s3	b	1.23 ± 0.18	SSS
130.....	9 55 38.62	68 49 22.9	10.98 ± 1.48	4.09	...	s1	D <sub>25</sub>	1.49 ± 0.20	
131.....	9 55 40.69	69 01 05.0	3.20 ± 0.80	3.21	>HST	s3	b	0.43 ± 0.11	
132.....	9 55 42.21	69 03 36.3	800.98 ± 12.62	53.88	21.67	s3	b	30.00 ± 1.00	SSS, H25
133.....	9 55 42.86	69 03 07.6	21.84 ± 2.08	8.82	...	s3	b	3.60 ± 1.70	
134.....	9 55 43.17	69 04 45.0	5.91 ± 1.08	4.21	>HST	s3	b	0.80 ± 0.15	
135.....	9 55 43.34	69 04 23.2	2.92 ± 0.76	3.33	>HST	s3	b	0.40 ± 0.10	
136.....	9 55 43.76	68 59 04.8	38.18 ± 2.75	11.44	...	s3	d	4.00 ± 0.40	H27
137.....	9 55 44.63	69 10 05.2	14.50 ± 1.70	6.80	>20.77	s4	d	2.65 ± 0.31	
138.....	9 55 44.71	69 05 34.5	12.12 ± 1.55	6.17	22.77	s3	d	1.65 ± 0.21	
139.....	9 55 45.91	69 03 00.4	14.70 ± 1.71	7.13	>17.60	s3	b	2.00 ± 0.23	
140.....	9 55 46.16	68 53 40.7	3.87 ± 0.88	3.27	...	s2	d	0.71 ± 0.16	
141.....	9 55 47.05	69 05 51.1	66.39 ± 3.63	15.28	18.63	s3	d	11.80 ± 1.30	H28, H II, GC
142.....	9 55 47.96	68 59 28.2	6.11 ± 1.10	4.52	...	s3	d	0.83 ± 0.15	SSS, H II
143.....	9 55 48.19	68 59 15.1	4.22 ± 0.92	3.88	>21.00	s3	d	0.57 ± 0.12	SSS
144.....	9 55 49.41	68 58 36.3	52.30 ± 3.22	13.31	...	s3	d	14.50 ± 1.50	H29, P40, SNR
145.....	9 55 49.52	69 08 12.0	78.12 ± 3.94	16.74	...	s4	d	14.80 ± 1.60	H30, P42
146.....	9 55 49.87	69 05 32.0	428.91 ± 9.23	39.54	20.77	s3	d	59.80 ± 1.60	X7, H31, P41, GC
147.....	9 55 51.54	69 04 10.5	2.61 ± 0.72	2.86	...	s3	b	0.36 ± 0.10	
148.....	9 55 51.58	69 07 43.1	3.27 ± 0.81	3.26	18.81	s4	d	0.60 ± 0.15	H II, GC
149.....	9 55 53.13	69 05 20.1	35.05 ± 2.64	11.05	22.20	s3	d	1.00 ± 0.00	SSS
150.....	9 55 53.31	69 02 06.5	14.22 ± 1.68	7.02	...	s3	b	1.93 ± 0.23	
151.....	9 55 53.68	69 04 34.8	7.00 ± 1.18	4.60	24.28	s3	d	0.95 ± 0.16	
152.....	9 55 55.01	69 02 38.9	4.30 ± 0.93	3.77	...	s3	b	0.59 ± 0.13	
153.....	9 55 55.37	68 58 58.5	2.49 ± 0.70	2.86	...	s3	d	0.34 ± 0.10	
154.....	9 55 55.79	69 10 08.5	9.00 ± 1.34	5.31	...	s4	d	1.65 ± 0.24	
155.....	9 55 56.11	69 03 12.2	6.46 ± 1.13	4.87	...	s3	b	0.88 ± 0.15	SSS, Radio
156.....	9 55 56.21	69 05 14.7	9.16 ± 1.35	5.56	23.56	s3	d	1.25 ± 0.18	
157.....	9 55 56.74	69 08 02.6	5.84 ± 1.08	4.25	20.5(I)	s4	d	1.07 ± 0.20	Extended?
158.....	9 55 58.61	69 05 26.2	64.07 ± 3.57	15.11	26.37	s3	d	16.00 ± 1.70	H32, GC
159.....	9 55 59.15	69 06 17.4	20.14 ± 2.00	8.19	25.28	s3	d	2.10 ± 0.50	
160.....	9 56 01.97	68 58 59.3	44.41 ± 2.97	12.81	...	s3	d	2.00 ± 0.30	H33, P43
161.....	9 56 02.69	68 59 35.2	40.46 ± 2.84	12.24	...	s3	d	3.40 ± 1.10	H34
162.....	9 56 02.78	68 58 44.0	12.85 ± 1.60	6.88	...	s3	d	1.75 ± 0.22	
163.....	9 56 03.15	69 02 16.8	4.81 ± 0.98	4.06	...	s3	d	0.65 ± 0.13	
164.....	9 56 03.29	69 01 07.3	3.77 ± 0.87	3.64	...	s3	d	0.51 ± 0.12	
165.....	9 56 04.36	69 11 59.7	5.81 ± 1.07	3.43	...	s4	d	1.06 ± 0.20	
166.....	9 56 04.69	68 58 39.2	2.90 ± 0.76	3.24	...	s3	d	0.39 ± 0.10	
167.....	9 56 04.93	69 03 43.7	2.61 ± 0.72	2.90	>19.09	s3	d	0.36 ± 0.10	H II
168.....	9 56 06.07	68 59 40.7	5.66 ± 1.06	4.54	...	s3	d	0.77 ± 0.14	H II
169.....	9 56 06.09	69 08 33.5	6.72 ± 1.16	4.67	...	s4	d	1.23 ± 0.21	
170.....	9 56 07.84	69 03 25.2	15.10 ± 1.73	7.08	...	s3	d	2.05 ± 0.24	
171.....	9 56 09.05	69 01 06.4	110.56 ± 4.69	20.30	...	s3	d	4.00 ± 0.50	SSS, H36, P44
172.....	9 56 09.48	69 12 49.5	22.46 ± 2.11	8.32	...	s4	D <sub>25</sub>	5.10 ± 0.80	H35, P45
173.....	9 56 13.74	69 06 30.6	21.10 ± 2.05	8.07	24.75	s3	d	2.87 ± 0.28	H37, P46
174.....	9 56 14.21	69 02 24.3	4.02 ± 0.89	3.58	>19.05	s3	d	0.55 ± 0.12	SSS, H II
175.....	9 56 14.42	69 02 47.9	13.66 ± 1.65	6.81	...	s3	d	1.86 ± 0.22	
176.....	9 56 14.85	69 03 37.7	3.48 ± 0.83	3.36	...	s3	d	0.47 ± 0.11	H II
177.....	9 56 27.46	69 10 12.1	22.57 ± 2.12	8.46	...	s4	D <sub>25</sub>	3.10 ± 0.50	

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 2 is also available in machine-readable form in the electronic edition of the *Astrophysical Journal Supplement*.

threshold. This intermediate value means that up to one noise peak in the region far from the aimpoint may be falsely identified as a true source. Inspection of the on-axis region of the image showed that no sources were erroneously overlooked using the S/N threshold of 2.8.

The PSF used in the search can have any shape and the source-finding algorithm allows either a mathematical model PSF or a high-fidelity simulated PSF available from

the CXC PSF library.<sup>6</sup> A circular Gaussian approximation to the PSF does a good job of locating sources, in comparison to simulated PSFs, assuming the width of the Gaussian increased quadratically off-axis so that the size of the Gaussian roughly matches the observed off-axis broadening of a

<sup>6</sup> Available from <http://cxc.harvard.edu/caldb/download.html>.

point source image. This is not unexpected since bright sources are easily detected in any method and, for faint sources, Poisson noise removes the importance of the exact PSF shape. Assuming a circular Gaussian PSF gives higher weight to sources with a central concentration of events. This is superior to a cell detect method which only looks for an excess of counts in an arbitrary source region and does not depend on the distribution of events within the region.

The source detection process was repeated using the CXC source detection tool “wavdetect” (Freeman et al. 2002). The wavdetect tool is similar to our method in that it is more likely to detect sources with a central condensation. wavdetect was applied on spatial scales from 1 to 16 pixels in logarithmic steps using a significance threshold for source detection corresponding to less than a  $10^{-6}$  chance probability of detection due to local background fluctuations. The results were consistent with our method at the equivalent significance level.

Point-source counts and spectra were extracted from within the 95% encircled-energy aperture of the model PSF. Background regions were typically chosen from annular regions surrounding the source regions except in crowded regions of the field where background regions adjacent to the source were used. The background-subtracted counts within the source regions were scaled to obtain the aperture-corrected count values. The background-subtracted point source detection limit is 12 counts for the 2.8 minimum S/N threshold and a minimum  $5\sigma$  above background. The resulting source positions, count rates, and S/N ratios are listed in columns (2)–(5), respectively, of Table 2.

### 3.2. Counterparts and Source Identifications

Optical properties of the X-ray sources were determined using archival *HST* WFPC2 images, the catalog (complete to  $V \leq 21$ ) of Perelmuter & Racine (1995), and Digitized Sky Survey (DSS) images. Additionally, compilations of supernova remnant (SNR) candidates (Matonick & Fesen 1997), H II regions (Petit et al. 1988; Kaufman et al. 1987), globular clusters (Perelmuter, Brodie, & Huchra 1995; Chandar et al. 2001), novae (Shara, Sandage, & Zurek 1999), and stellar objects (Zickgraf & Humphreys 1991; Ivanova 1992; Zickgraf, Szeifert, & Humphreys 1996; Sholukhova et al. 1998) were queried for spatial correlations to the X-ray sources. Objects within the  $3\sigma$  uncertainty of the X-ray source positions are considered potential counterparts to the X-ray sources.

Archival *HST* WFPC2 images of portions of the *Chandra* field were searched for potential optical counterparts to the X-ray sources based on spatial coincidence. For most of the images there were  $V$ -type filters (F555W, F606W, and F547M) available. For a subset of these observations there were images with filters corresponding approximately to standard  $U$  (filter F336W),  $B$  (F439W),  $V$  (F555W),  $R$  (F675W), and  $I$  (F814W) for each field. When there were multiple images, using the same filter, they were combined using the IRAF task “crrej” to remove cosmic ray contamination. For a few images in which there was a position offset the task “xregister” was used to create matching images and the task “gcombine” was used to combine the images and to remove cosmic rays. A list of point sources detected in each field in a  $V$  filter image was generated using the star-finding algorithm “daofind” in DAOPHOT (Stetson 1987). Photometry was performed for each source using a

$0''.3$  radius aperture and concentric background annuli of inner radius  $1''.0$  and  $0''.5$  width. For extended sources, a radius as large as  $1''.0$  was needed for the source aperture. Where multiple optical objects fall within the  $3\sigma$  width of the *Chandra* model PSF at the location of an X-ray source, we selected the most probable candidate optical source based on (in order of preference) optical brightness, colors, or distance from the X-ray source centroid.

A total of 66 X-ray sources lie within one or more of the *HST* imaging fields. Of these sources, 34 have potential optical counterparts based on spatial coincidence with an average separation between X-ray source and optical candidate of  $\sim 1.5\sigma$ . Forty-three of the 66 sources lie in the bulge of M81, and 13 of these have optical candidates. In contrast, 21 disk sources are within the *HST* fields, and 19 of these have optical candidates based on spatial coincidence. The search for optical candidates was repeated using an artificial distribution of X-ray source positions and position uncertainties (while preserving the radial distribution of sources). Of 89 artificial X-ray sources, 51 fell within one or more of the *HST* imaging fields and 16 of these had optical candidates (five candidates in the bulge of 36 possible and 11 candidates in the disk of 15 possible). Thus, we expect about  $20 \pm 4$  of the 34 X-ray sources with potential optical counterparts are simply chance coincidence with a greater probability of chance coincidence for sources in the disk. Nevertheless, the *HST* observations place valid upper limits to the optical luminosity of the X-ray sources located within their fields.

The apparent visual magnitudes of the optical candidates (from F555W, F606W, or F547M filter measurements) are listed in column (6) of Table 2. The values have not been corrected for charge transfer efficiency (CTE) effects nor color-corrected to obtain true Johnson  $V$  magnitudes. CTE effects are estimated to be of order 0.01 mag, while the color-correction depends on the intrinsic properties of the source and on interstellar reddening. The correction is typically less than 0.3 mag. For two of the sources, numbers 52 and 157, only F814W ( $I$ -band) images were available, and they are denoted as such in column (6) of Table 2. Potential optical counterparts to seven X-ray sources appear extended in the *HST* images. Three of these are listed as globular clusters in the catalog of Chandar et al. (2001, see below). Two others, source numbers 82 and 127, are probably also globular clusters (see below). The remaining two sources that appear extended in the *HST* images are denoted “Extended?” in column (10) of Table 2. X-ray sources located within *HST* fields but without optical candidates are designated as “>*HST*” in column (6) of Table 2 to indicate they are fainter than the *HST* limiting magnitude of  $\sim 27$  mag. Visual magnitudes of objects in the Perelmuter & Racine (1995) catalog within  $3\sigma$  of X-ray sources are listed as upper limits in column (6) of Table 2 unless superseded by *HST*-derived values.

Archived radio observations were used to search for potential radio counterparts to the X-ray sources. Radio data obtained using the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO)<sup>7</sup> as part of an on-going study of SN 1993J were kindly provided by N. Bartel and M. Beitenholz for our use. For the present

<sup>7</sup> The NRAO is a facility of the National Science Foundation operated under a cooperative agreement by Associated Universities, Inc.

work, we analyzed a radio map made from a 1999 November 23 observation at a wavelength of 6 cm (4985 MHz) in the B configuration. The angular resolution is approximately  $1''.5$ , and the root mean square noise level is  $25 \mu\text{Jy}$ . The image was prepared using standard radio data reduction techniques using the NRAO software package AIPS (Astronomical Image Processing System). The field of view of the radio map is approximately  $8'.5 \times 8'.5$  centered on the optical nucleus of the galaxy. Of the 177 *Chandra*-detected X-ray sources, 91 fell within this field of view. The two most luminous radio sources in the field of view are the nucleus and SN 1993J, and both of these sources are known to be time variable in their radio emission. Only two other X-ray sources were clearly detected above the  $3 \sigma$  level in these radio data, source numbers 79 ( $55 \pm 17 \mu\text{Jy}$ ) and 155 ( $95 \pm 26 \mu\text{Jy}$ ). They are designated “Radio” in column (10) of Table 2. A source at the location of *Einstein* source X6 was detected at 3.6 cm, as discussed in § 4.2. Further analysis of the radio properties of the X-ray sources will be the subject of a separate paper (T. Pannuti et al. 2003, in preparation).

There are five SNRs in the tabulation of Matonick & Fesen (1997) coincident with X-ray sources including *Einstein* source X6. As discussed in § 4.2, the X-ray emission from X6 is not from a SNR. All four remaining SNR candidates are located along spiral arms, as expected for core-collapse supernovae from young massive stars, and are listed with the designation “SNR” in column (10) of Table 2.

There are no X-ray sources coincident with any of the 25 globular clusters identified by Perelmuter et al. (1995). The positions of four globular clusters in the tabulation by Chandar et al. (2001) are within the  $3 \sigma$  error circle of X-ray sources as listed in column (10) of Table 2, with the designation “GC.” Three of these, corresponding to X-ray source numbers 141, 146, and 158, are located near a prominent spiral arm, yet the colors reported by Chandar et al. (2001) place the optical candidates among the typical population of old ( $\geq 1$  Gyr) clusters. The remaining candidate, corresponding to number 148 of Table 2, is also an old globular cluster but its projected position is between spiral arms. In addition, one of the bright objects in the catalog of Perelmuter & Racine (1995) that is coincident with X-ray sources has an optical magnitude  $18 \leq V \leq 21$  and colors in the ranges  $0.5 \leq (B-V) \leq 1.1$  and  $0.3 \leq (V-R) \leq 0.7$ . This object, source number 127, meets the criteria given by Perelmuter et al. (1995) for globular cluster candidates and is designated “GC?” in column (10) of Table 2. Also listed with the same designation are X-ray source numbers 67 and 82. Although the optical candidates of both objects exceed the Perelmuter & Racine (1995) brightness criteria, Ghosh et al. (2001) have argued that they are very likely globular clusters (see also § 4.4).

Three hundred and ninety of the 492 H II regions tabulated by Petit et al. (1988) are within the ACIS imaging field of view. Twelve of these are coincident with *Chandra* X-ray sources. All are located along M81 spiral arms. They are designated “H II” in column (10) of Table 2.

Three *Chandra* sources are coincident with foreground stars. These are labeled with a designation “\*” in column (10) of Table 2. Two of these, X-ray source numbers 56 and 60, are the PPM cataloged stars used to determine absolute X-ray source positions (Table 1). Inspection of DSS images to search for uncataloged bright star-like objects revealed no additional foreground star candidates. X-ray source

number 8, however, is very likely a background galaxy based on its shape in DSS images.

### 3.3. X-Ray Spectral and Timing Analysis

Statistically constrained model fits could be achieved for a total of 39 sources in the M81 field. Detailed X-ray properties of SN 1993J, *Einstein* source X6, and the nucleus are presented in § 4 and of the three brightest supersoft sources in Swartz et al. (2002). Best-fit spectral model parameters for the remaining 33 bright sources are listed in Table 3.

The X-ray spectra of these 33 sources were fitted with absorbed power-law models characterized by the photon index  $\Gamma$ ; with absorbed Raymond-Smith spectral models representing emission from low density, optically thin plasma characterized by the temperature  $kT$ ; and with absorbed blackbody models. The metal abundances in the thermal plasma models were assumed to be 3% of their solar value consistent with the results of Kong et al. (2000) for the galaxy as a whole. Spectra were grouped to contain a minimum of 20 counts per spectral bin and fitted with models using the XSPEC spectral fitting package (Arnaud 1996).

The power-law model provides a significantly better fit to all but two of the X-ray sources. The two exceptions, X-ray source numbers 160 and 161, are best fitted with blackbody spectral models with effective temperatures 0.2 and 0.57 keV, respectively. The best-fit absorption column density, power-law index (or blackbody temperature), fit statistic, and unabsorbed 0.3–8.0 keV luminosities are listed in columns (2)–(5) of Table 3. Quoted errors are 90% confidence limits for a single interesting parameter based on the  $\chi^2$  fit statistic. Absorption column densities were constrained in the fitting procedure to be at least as large as the Galactic column density along the line of sight to M81. This resulted in a best-fit value of  $N_{\text{H}}$  equal to this lower limit for eight sources. Therefore, the column densities are listed as  $N_{\text{H}} = 4.0 \pm 0.0$  in column (2) of Table 3 for these sources.

The luminosities for the remaining sources in Table 2 were estimated assuming an absorbed power-law spectrum with photon index  $\Gamma = 1.5$  and hydrogen column density  $N_{20} = N_{\text{H}}/10^{20} = 11.0 \text{ cm}^{-2}$ . These are the average values for the 31 sources in Table 3, whose spectra are best fitted with a power-law model. For comparison, the Galactic hydrogen column density in the direction of M81 is  $N_{20} = 4.0 \text{ cm}^{-2}$  (Stark et al. 1992). The source detection limit of 12 counts corresponds to an observed flux of  $F_{0.3-8 \text{ keV}} = 1.9 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}$  for sources on device S3 ( $F_{0.3-8 \text{ keV}} = 2.5 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}$  on FI devices) or an unabsorbed 0.3–8 keV luminosity of  $L_{\text{X}} = 3.4(4.5) \times 10^{36} \text{ ergs s}^{-1}$  for sources on the BI (FI) devices. The luminosities of all sources are listed in column (9) of Table 2.

The Kolmogorov-Smirnov statistic was used to test these sources (including background) for constant count rates over the duration of the primary observation. The Kolmogorov-Smirnov statistic results are listed in column (6) of Table 3. Sources with a low value of  $P_{\text{KS}}$  have a high probability of being variable.

The 0.3–8.0 keV light curves were used to estimate the overall X-ray power density spectrum (PDS) of the X-ray sources listed in Table 3. Light curves were sampled at the 3.24104 s nominal ACIS frame time and used to compute the Leahy-normalized power spectra of each source. The average power in each normalized-PDS was 2.0, which is consistent with what is expected from Poisson noise (Leahy

TABLE 3  
M81 BRIGHT X-RAY SOURCES

Number (1)	$N_{\text{H}}$ ( $10^{20} \text{ cm}^{-2}$ ) (2)	Spectral Parameter <sup>a</sup> (3)	$\chi^2/\text{dof}$ (4)	$L_{\text{X}}$ ( $10^{37} \text{ ergs s}^{-1}$ ) (5)	$P_{\text{KS}}$ (6)
37.....	27.2 ± 19.0	1.63 ± 0.60	2.03/5	6.3 ± 1.1	74.50
51.....	14.9 ± 10.0	1.76 ± 0.42	5.36/8	5.0 ± 0.6	81.80
52.....	13.6 ± 4.0	1.59 ± 0.14	38.87/38	27.0 ± 0.6	65.10
57.....	99.1 ± 40.0	1.90 ± 0.51	8.00/13	22.0 ± 2.8	12.10
67.....	4.0 ± 0.0	1.31 ± 0.28	4.42/4	3.5 ± 0.7	1.89
69.....	11.8 ± 3.0	1.47 ± 0.11	58.11/43	26.7 ± 1.0	58.50
81.....	13.5 ± 7.0	2.32 ± 0.35	14.01/7	4.8 ± 0.5	45.90
82.....	10.0 ± 10.0	1.43 ± 0.55	3.65/8	5.1 ± 1.1	53.40
83.....	14.4 ± 4.0	1.79 ± 0.13	60.26/35	22.0 ± 0.9	92.60
86.....	4.0 ± 0.0	1.08 ± 0.13	42.43/35	35.0 ± 3.0	4.03
93.....	15.6 ± 7.0	2.03 ± 0.45	1.98/4	3.7 ± 0.5	59.80
95.....	4.0 ± 0.0	1.61 ± 0.17	14.45/11	5.7 ± 0.6	17.60
102.....	4.0 ± 0.0	1.80 ± 0.24	12.14/11	6.8 ± 0.6	82.00
109.....	9.7 ± 5.0	2.20 ± 0.33	8.81/7	4.2 ± 0.4	70.30
112.....	4.0 ± 0.0	1.17 ± 0.16	13.81/8	5.8 ± 0.6	70.30
113.....	14.2 ± 10.0	2.24 ± 0.50	6.54/8	4.3 ± 0.5	9.76
115.....	7.7 ± 7.0	1.26 ± 0.85	2.22/4	3.1 ± 0.5	25.40
116.....	8.7 ± 3.0	1.44 ± 0.12	32.71/30	19.5 ± 1.0	68.70
117.....	16.0 ± 13.0	1.92 ± 0.43	6.49/6	6.0 ± 1.0	58.20
118.....	5.2 ± 3.0	1.53 ± 0.25	13.28/12	7.4 ± 0.5	99.10
120.....	11.5 ± 5.0	2.57 ± 0.50	8.00/5	3.6 ± 0.6	98.40
126.....	4.0 ± 0.0	1.71 ± 0.15	30.69/14	6.4 ± 1.0	56.30
133.....	24.5 ± 20.0	2.15 ± 0.80	1.16/6	3.6 ± 1.7	21.00
136.....	10.3 ± 5.0	1.95 ± 0.47	7.68/8	4.0 ± 0.4	91.00
141.....	12.3 ± 7.0	1.22 ± 0.20	8.84/15	11.8 ± 1.3	22.90
144.....	13.6 ± 5.0	2.61 ± 0.39	12.15/8	14.5 ± 1.5	0.61
145.....	4.0 ± 0.0	1.41 ± 0.18	18.82/22	14.8 ± 1.6	72.40
146.....	11.5 ± 2.0	1.37 ± 0.08	72.49/81	59.8 ± 1.6	5.31
158.....	28.7 ± 11.0	3.61 ± 0.96	19.33/13	16.0 ± 1.7	35.50
159.....	17.4 ± 17.0	2.13 ± 1.10	6.88/3	2.1 ± 0.5	38.10
160.....	4.0 ± 0.0	0.20 ± 0.02	11.89/7	2.0 ± 0.3	37.70
161.....	38.3 ± 15.0	0.57 ± 0.14	10.64/9	3.4 ± 1.1	71.70
172.....	10.0 ± 6.3	1.21 ± 0.37	4.37/7	5.1 ± 0.8	2.58

<sup>a</sup> Power-law photon index,  $\Gamma$ , except for source numbers 160 and 161, where spectral parameter is blackbody temperature,  $kT$ , in keV.

et al. 1983). Fluctuations up to 10–15 are commonly seen in the normalized power spectra with a maximum power in one or two frequency bins typically between 15 and 20 for all the sources with one exception. Fluctuations of this order are due to noise. For the one exception, X-ray source number 69, the average normalized-PDS power was 2.0 and the power of all the frequencies was less than 15 except at 0.0245 Hz (corresponding to a 40.8 s period), which has a power of 28. Given that there are 4096 frequency bins in the PDS for each of 33 sources, the probability of seeing one peak with power 28 is 12%. Therefore, we conclude that the detection of the peak with power 28 could be a statistical fluctuation and that no X-ray pulsations are detected in any of the sources with the existing data.

#### 4. INDIVIDUAL M81 SOURCES

The 11 brightest sources in the *Chandra* field appear to exceed the Eddington limit luminosity for a  $1.5 M_{\odot}$  spherically accreting object. It should be noted that many accreting compact sources in our Galaxy and in the Magellanic Clouds that exceed the Eddington limit are in fact neutron stars with episodes of high X-ray luminosity

(see, e.g., the compilation in Grimm, Gilfanov, & Sunyaev 2001). The four brightest sources in M81 are SN 1993J, *Einstein* source X6, the nucleus, and the brightest supersoft source candidate. The supersoft source is discussed in detail by Swartz et al. (2002), and no further analysis is given here. Details of the other three sources are given in the following subsections followed by a brief discussion of the remaining bright sources (§ 4.4).

##### 4.1. SN 1993J

Supernova (SN) 1993J was discovered 1993 March 28 and was observed by *Chandra* 2594 days after outburst. The pre-supernova star was likely a  $\sim 17 M_{\odot}$  star that lost all but  $\sim 0.2$ – $0.4 M_{\odot}$  of its hydrogen envelope prior to explosion (see Wheeler & Filippenko 1996 for an early review). This mass was lost through a combination of stellar winds and mass transfer to a binary companion, possibly involving a common envelope phase (Podsiadlowski et al. 1993; Woosley et al. 1994; Nomoto, Iwamoto, & Suzuki 1995). A circumstellar medium (CSM), a relic of this mass loss, surrounded the system at the time of explosion as evidenced by its early radio (Van Dyk et al. 1994) and X-ray signatures (e.g., Zimmerman et al. 1994).

Monitoring of this emission has continued since discovery. X-ray observations by *ROSAT* (Immler, Ashenbach, & Wang 2001) and *ASCA* (Uno et al. 2002) began 6 and 8 days after the explosion and continued intermittently for 1817 and 564 days, respectively. Radio monitoring continues (e.g., Marcaide et al. 1997; Bietenholz, Bartel, & Rupen 2001). The evolution of optical line profiles also shows an increasing contribution from SN debris interacting with surrounding gas (Patat, Chugai, & Massali 1995; Houck & Fransson 1996; Matheson et al. 2000).

The early X-ray and radio data have been successfully explained in terms of the circumstellar interaction model (Fransson, Lundqvist, & Chevalier 1996). In this model, the radial flow in free expansion of the SN debris steepens into a shock wave in the CSM, heating this gas to  $T \sim 10^9$  K. This outer shock cannot be freely expanding, so the supernova ejecta interacts with the hot gas and a second (inner, or reverse) shock front develops. The lower temperature ( $T \lesssim 10^8$  K) reverse shock gas dominates the soft X-ray emission with a flux dependent on the density gradient of the SN ejecta and on absorption in the cooling, postshock, gas.

#### 4.1.1. The Chandra X-Ray Spectrum of SN 1993J

The observed X-ray spectrum of SN 1993J, the best-fit model spectrum ( $\chi^2 = 94.6$  for 90 dof), and the fit residuals are shown in Figure 1. Models were applied to the spectrum in the energy range 0.3–5.0 keV because of a lack of signal at higher photon energies, including in the Fe K band at  $\sim 6.5$  keV. The model consists of two low-temperature absorbed thermal emission-line (*vmekal*) components, at  $0.35 \pm 0.06$  keV and  $1.01 \pm 0.05$  keV, both with  $N_{20} = 40.5 \pm 0.9$  cm $^{-2}$ ; and a high-temperature *mekal* component with  $kT = 6.0 \pm 0.9$  keV,  $N_{20} = 4.9 \pm 0.1$  cm $^{-2}$ . Abundances in the low-temperature components are consistent with solar values with the exception of N (15 times solar, though see below), Mg (0.2), Si (1.4), Fe (1.6) and He, C, O, and Ne,

which are all consistent with an abundance of zero. The high-temperature component is consistent with subsolar abundances but is not sensitive to this parameter.

The two low-temperature components are needed to fit the two peaks present in the observed spectrum (at  $0.78 \pm 0.02$  and  $0.98 \pm 0.02$  keV, respectively, Fig. 1). These peaks are dominated by Fe L emission from different ionization stages of Fe at the different temperatures. In addition, He-like Si and Mg (from the 0.35 keV component) and He-like S, and H-like Si and Mg (from the 1.01 keV component) are observed in the data. Notably absent is the O VIII Ly $\alpha$  line at 654 eV. This line is predicted to be strong over a range of plasma temperatures from  $\sim 0.1$  to 0.5 keV (e.g., Nahar 1999). The high-temperature component is needed to account for X-ray flux above  $\sim 1.5$  keV. No emission lines are produced by this component. In fact, replacing the *mekal* component with a bremsstrahlung model at the same temperature provides an equally acceptable fit to the spectrum.

The elemental abundances were allowed to vary in the two low-temperature component model fits (with the abundances and absorbing columns constrained to be equal between the two components). Beginning with solar ratios, the abundance of each element was individually varied while holding the abundances of the remaining elements fixed at their current values until the model converged. This procedure was repeated for all  $\alpha$ -chain elements from He through Ni and for N, Na, and Al. The largest reductions in  $\chi^2$  occurred for N, O, and Fe. A large N abundance is required to fit a broad feature near the N VII Ly $\alpha$  line at 0.5 keV. This feature lies just below the neutral O absorption edge at 0.53 keV and may, instead, be an artifact of a deeper O edge. This interpretation is also more consistent with evolutionary models of a massive progenitor star (e.g., Thielemann, Nomoto, & Hashimoto 1996) that do not predict an overabundance of N. The model requires no O consistent with the lack of observed O VIII Ly $\alpha$ . The overabundance of Fe

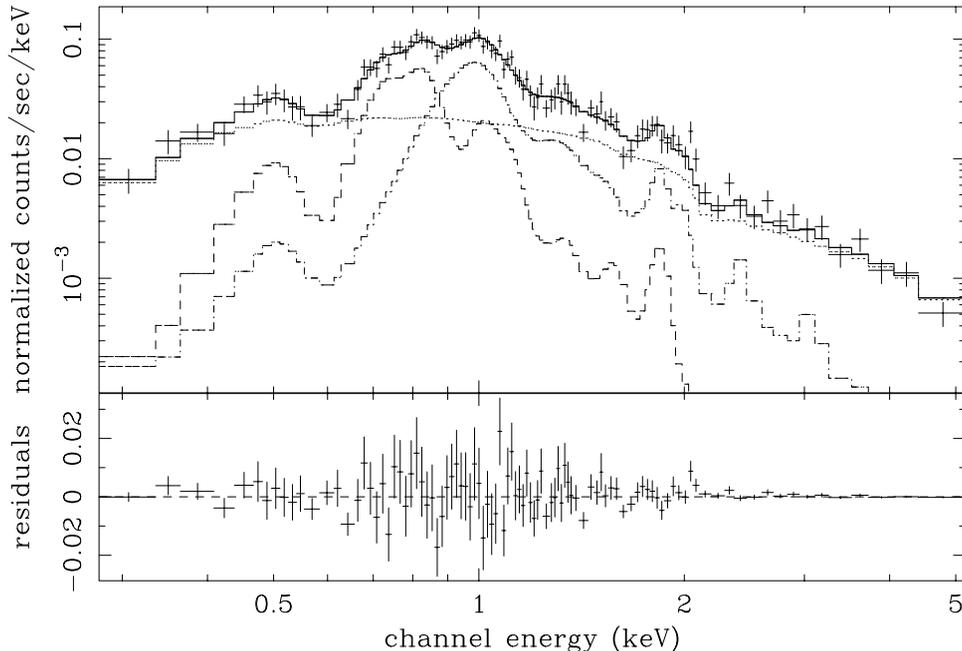


FIG. 1.—Observed X-ray spectrum of SN 1993J (*top*) and model fit residuals (*bottom*). Curves trace the full model (*solid line*), 0.35 keV (*dashed line*) and 1.01 keV (*dot-dashed line*) *vmekal* components, and the harder, 6.0 keV, *mekal* component (*dotted line*).

needed to fit the spectrum may indicate some of the explosively synthesized material has been transported to the outer regions of the SN ejecta which are presently entering the reverse-shock region.

The combination of low- and high-temperature components is consistent with the standard CSM interaction model. The low-temperature emission in this scenario originates in the reverse shock region, while the hard component comes from the much hotter forward shock. The low-temperature components are more heavily absorbed than the hard component consistent with an intervening dense cool shell of gas at the contact discontinuity between the forward and reverse shock fronts. The reverse shock front is distorted by Rayleigh-Taylor instabilities (Chevalier & Blondin 1995). Emission from regions of differing densities (and, hence, cooling rates) will have different characteristic temperatures. The two low-temperature model components may therefore only approximate a range of temperatures present in the reverse shock region.

In contrast, the forward shock is located further from the high-density contact region. High-resolution VLBI images (e.g., Bietenholz et al. 2001) shows the outer shell to be highly circular. While a single temperature forward shock may be favored in this case, we note that the temperature of the high-temperature component is uncertain due to the lack of signal above  $\sim 5$  keV. The relatively low temperature of this component,  $\sim 7 \times 10^7$  K, suggests relatively flat ejecta and CSM density profiles at the time of the *Chandra* observation.

The average densities in the reverse shock region and in the intervening absorbing shell can be estimated from the model parameters. The radius of the interaction region at 2594 days was approximately  $2 \times 10^{17}$  cm based on extrapolating the observed angular size at 1893 days (Bartel et al. 2000) to the time of the *Chandra* observation and assuming an average velocity of  $\sim 7000$  km s $^{-1}$  (Matheson et al. 2000) during the interval. The width of the shell is of order 10% of this radius. The number density in the thermal emission region is then  $\sim 5 \times 10^4$  cm $^{-3}$ , and that in the cool absorbing shell is  $\sim 2 \times 10^5$  cm $^{-3}$ . This implies the mass in the shell is of order  $\sim 0.4$  to  $2.0 M_{\odot}$ . The lower value is consistent with the value of  $\sim 0.3 M_{\odot}$  inferred from the deceleration observed in radio images of SN 1993J at an age of  $\sim 5$  yr (Bartel et al. 2000).

Conceivably, an underlying neutron star could also contribute to the hard emission detected from SN 1993J. While the dynamics of the hot, radioactively heated, gas at the center of the SN is unknown, accretion at a rate above a few  $10^{-8} M_{\odot}$  yr $^{-1}$  creates substantial X-ray emission. However, the emission in the *Chandra* band will be absorbed by the overlying SN debris. Assuming for simplicity a uniform-density expanding sphere of gas, the ejecta provides a total column density of order  $10^{22}$  cm $^{-2}$  per solar mass of ejecta at the time of the *Chandra* observation. Most of this material is in the form of metals. Thus, the effective hydrogen column is orders of magnitude higher. Woosley, Pinto, & Hartmann (1989) predicted no detectable X-ray flux below  $\sim 10$  keV from an accreting neutron star in the center of SN 1987A at an age of 2500 days with the exception of the Fe K $\alpha$  fluorescence line. A similar conclusion was reached by Xu et al. (1988). Though the amount of material ejected by SN 1993J is nearly an order of magnitude less than in SN 1987A, there is as yet no compelling evidence of a neutron star in the X-ray spectrum of SN 1993J at an age of  $\sim 7$  yr.

#### 4.1.2. The X-Ray Light Curve of SN 1993J

The 0.3–8.0 keV luminosity of SN 1993J on day 2594 was  $4.8 \times 10^{38}$  ergs s $^{-1}$ . The flux in the 0.1–2.4 keV *ROSAT* and 1–10 keV *ASCA* energy bands are  $\sim 3.3 \times 10^{38}$  and  $\sim 3.6 \times 10^{38}$  ergs s $^{-1}$ , respectively. *ROSAT* (Immler, Ashenbach, & Wang 2001) and *ASCA* (Uno et al. 2002) light curves, along with the *Chandra* data, are shown in Figure 2. Visual inspection shows that the light curves are not simple power laws but that the rate of decline of the X-ray luminosity increases after  $\sim 50$  to 100 days. The best-fit broken power-law model for the *ROSAT* light curve has its break at  $\sim 220$  days. The luminosity declines as  $L \propto t^{-0.24 \pm 0.04}$  prior to the break and as  $L \propto t^{-0.62 \pm 0.07}$  at later times. The break occurs at about 45 days in the *ASCA* energy range, but the change in slope is less pronounced, evolving from  $L \propto t^{-0.57 \pm 0.78}$  to  $L \propto t^{-0.84 \pm 0.24}$ .

As originally conceived, the self-similar form of the interaction model of Chevalier (1982; Fransson et al. 1996) applies only to the early phases of supernova evolution when both the SN ejecta and CSM density profiles can be represented by single power laws in radius. Extrapolation to  $\sim 7$  yr is inappropriate because, as the reverse shock progresses through the ejecta, the density profile flattens, while the forward shock has traversed some  $10^4$  yr of previous mass-loss history (assuming a wind velocity of order 10 km s $^{-1}$  and a shock velocity of order  $10^4$  km s $^{-1}$ ). Furthermore, the importance of radiative losses behind the reverse shock and departures from electron-ion equipartition in the forward shock make numerical calculations necessary.

Suzuki & Nomoto (1995) have performed hydrodynamic calculations based on models of the SN ejecta that accurately reproduce the observed optical light curve of SN 1993J (Nomoto et al. 1995). Suzuki & Nomoto (1995) followed the evolution for  $\sim 1000$  days and find reasonable agreement with X-ray observations for the first 50 days or more. Beyond that time, Suzuki & Nomoto (1995) require a combination of a steeper CSM density gradient and a clumpy CSM morphology to sustain a level of X-ray flux comparable to that observed. However, their models predict rapid increases in X-ray flux, followed by declines on time-scales of order months, as the forward shock sweeps through individual clumps. This is in contrast to the observed steady decline of the X-ray light curve over the entire monitoring sequence.

While beyond the context and scope of the present work, X-ray observations of SN 1993J warrant further investigation. As pointed out by Immler et al. (2001), X-rays from the interaction region trace the pre-SN evolution of the progenitor system and X-rays are a direct means of accessing this evolution in detail as has been undertaken recently for SN 1987A (Park et al. 2002).

#### 4.2. Einstein Source X-6

The brightest non-nuclear source in the *Chandra* field is the *Einstein*-discovered source X6 (Fabbiano 1988) located  $\sim 1'$  to the southeast of and along the same prominent spiral arm containing SN 1993J. The X-ray flux in the *Einstein* observation was  $9.5 \times 10^{-13}$  ergs cm $^{-2}$  s $^{-1}$ , placing X6 in the class of ultraluminous X-ray sources (ULXs) whose luminosities ( $\geq 10^{39}$  ergs s $^{-1}$ ) far exceed the Eddington limit for spherically accreting  $\sim 1.5 M_{\odot}$  objects. The X-ray flux from X6 has remained remarkably steady throughout its observed history. X6 is coincident with a weak radio source

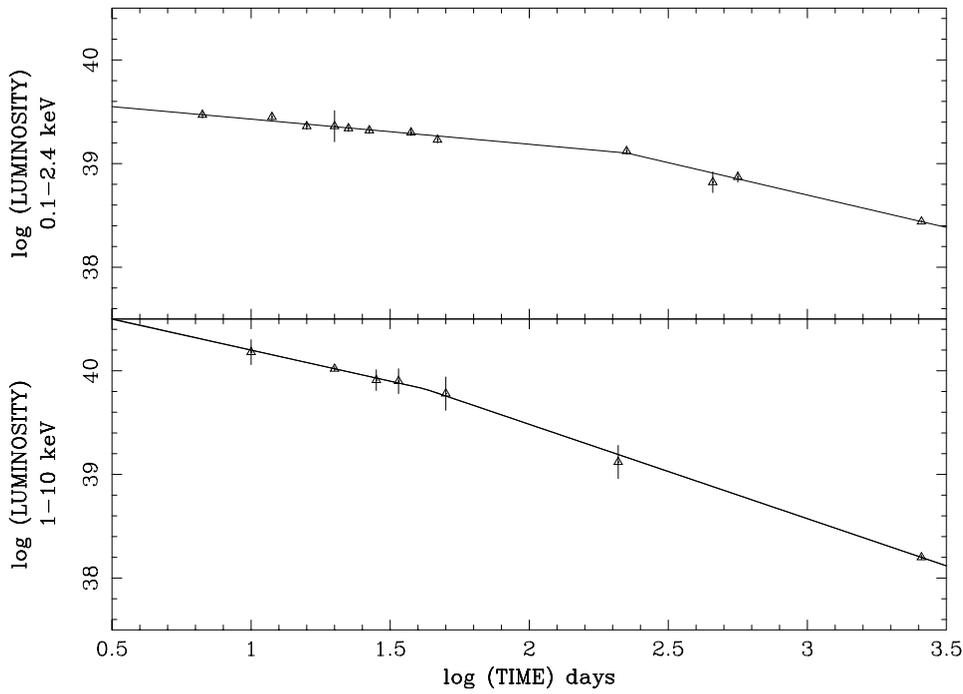


Fig. 2.—Observed X-ray light curve of SN 1993J in the *ROSAT* (top) and *ASCA* (bottom) energy bands. The best-fit broken power-law models are shown as solid lines.

(Fabbiano 1988) and with an optically identified SNR candidate (Matonick & Fesen 1997). *Chandra* can resolve sources on scales smaller than the 90 pc ( $5''$ ) diameter reported for the SNR.

#### 4.2.1. The *Chandra* X-Ray Spectrum of X6

The high X-ray flux from X6 leads to a pile-up of events in the ACIS detector and to statistically significant detection of events during frame transfer. Events detected during frame transfer appear as a streak or trail through the source along the detector readout direction. These events are not piled up and therefore represent the true count rate (when properly time-scaled) and source spectrum although spread over a large spatial region. The 0.3–8.0 keV count rate of X6 is 0.21 counts  $s^{-1}$  compared to the  $0.38 \pm 0.04$  counts  $s^{-1}$  rate deduced from the readout trail. The spectrum was fitted using two identical models but with one model convolved with the pile-up model developed by Davis (2001) as implemented in XSPEC v. 11.1.0u. This combination reflects contributions from pile-up and non-pile-up spatial regions: Piled-up events are localized to the central few pixels containing the majority of the detected counts. The spectral extraction region includes this central region and additional source counts from surrounding pixels. A linear energy grid is necessary to apply the convolution model. Therefore, the spectral analysis is performed with the Level 2 event data using CXC-provided response and ancillary response files instead of those provided by L. Townsley which utilize a piecewise linear energy grid. As a test of our procedures, we repeated the analysis of S5 0836+710 undertaken as a demonstration by Davis (2001) and derived model parameters consistent with the values presented in that paper.

Spectral models were applied to photons from X6 in the 0.3 to 10.0 keV range using a  $2''$  extraction region. The extension to 10 keV was made because there are substantial

source counts above 8 keV, and the observed spectrum shows a flattening above  $\sim 7$  keV characteristic of pile-up (Fig. 3), a feature helpful for constraining the model parameters. The  $2''$  extraction region is the same size region used by Davis (2001) in his analysis of S5 0836+710. The fitting procedure resulted in a slight adjustment of the pile-up parameters from the values reported in Davis (2001). The event grade morphing parameter,  $\alpha$ , and the fraction of the extraction region *not* experiencing pile-up,  $1 - f$ , both must be increased slightly because the PSF is slightly asymmetric and broadened at the  $\sim 1'$  off-axis position of X6 relative to the on-axis location of S5 0836+710. Inspection of the high-resolution image of the model PSF shows the asymmetry increases the probability that the second photon in a two-photon event will enter an adjacent pixel rather than a corner pixel and hence will be registered as a good grade. The broadening of the PSF results in a larger fraction of the detected photons falling in the wings of the PSF where pile-up does not occur. The resulting pile-up parameters are  $\alpha = 0.585$  compared to 0.5 used by Davis (2001) and  $1 - f = 0.063$  (compared to 0.05) as determined from the best-fit spectral model.

The best-fit model for the observed spectrum of X6 is an absorbed disk blackbody. Makishima et al. (2000) have modeled the *ASCA* spectrum of X6 and other ULXs using the disk blackbody model they developed (Mitsuda et al. 1984) for modeling the high soft state of accreting black holes. X-ray emission in this state originates from an optically thick accretion disk, and the model is basically a superposition of blackbody emission from different disk annuli with local disk temperatures scaling with the disk radius as  $R^{-3/4}$ . Thus, the model spectrum in the X-ray regime is dominated by the innermost disk temperature,  $T_{in}$ , with a normalization scaling as the disk geometry;  $K \propto (R_{in}/D)^2 \cos(\theta)$ , where  $R_{in}$  is the innermost disk radius,  $D$

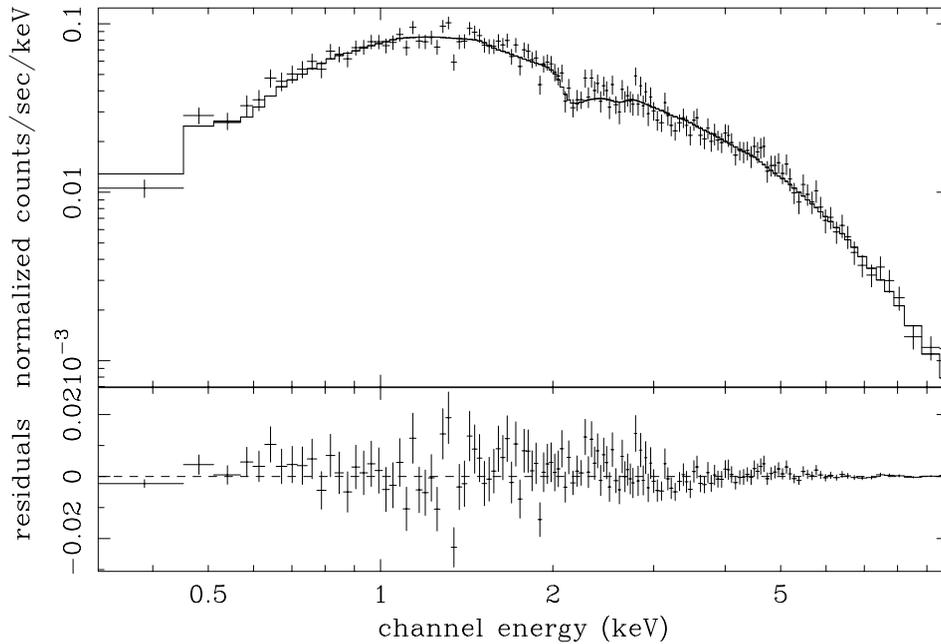


FIG. 3.—Observed X-ray spectrum of *Einstein* source X6 (*top*) and model fit residuals (*bottom*). The curve traces the best-fit disk blackbody model spectrum with pile-up modeled as in Davis (2001).

is the source distance, and  $\theta$  is the disk inclination. This model provides a fit statistic  $\chi^2 = 295.3$  for 283 dof. The best-fit innermost disk temperature is  $T_{\text{in}} = 1.03 \pm 0.11$  keV, the corresponding radius is  $R_{\text{in}} = 161 \pm 16$  km, and the absorbing column density is  $N_{20} = 21.7 \pm 1.0$  cm $^{-2}$ . The disk blackbody model parameters correspond to an 18  $M_{\odot}$  accreting, nonrotating, object and a bolometric luminosity of  $\sim 2.7 \times 10^{39}$  ergs s $^{-1}$  according to the relations given by Makishima et al. (2000). This luminosity is equivalent to the Eddington luminosity for the derived mass. The parameters obtained from analysis of the *ASCA* spectra (Mizuno 2000; Makishima et al. 2000) are  $T_{\text{in}} = 1.48 \pm 0.08$  keV,  $R_{\text{in}} = 83 \pm 8$  km, and  $N_{20} = 21 \pm 3$  cm $^{-2}$ . The higher temperature implies a lower mass since  $T_{\text{in}} \propto M^{-1/4}$  (eq. [12], Makishima et al. 2000) but a higher luminosity,  $L \propto R_{\text{in}}^2 T_{\text{in}}^4$ , implying the luminosity of X6 exceeds the Eddington limit. Makishima et al. (2000) argue that, if the compact object is a Kerr black hole, then the inner radius can be reduced by as much as a factor of 6, thereby reducing the derived bolometric luminosity to values below the Eddington limit for the temperature-estimated mass. In contrast, the fit parameters to the *Chandra* data lead to self-consistent values of bolometric luminosity, mass of the compact object, and the associated Eddington limit luminosity.

Mizuno (2000) analyzed seven individual *ASCA* observations of X6 and found a temperature  $T_{\text{in}} = 1.3 \pm 0.1$  keV in two of the observations and  $1.6 \pm 0.1$  keV in the remaining observations. The value derived here,  $T_{\text{in}} = 1.0 \pm 0.1$  keV, is significantly lower than these values. It is unclear if this is a real effect or is an artifact of the pile-up model.

A power-law model fitted to the *Chandra* spectrum was statistically less acceptable. The best-fit result with  $\alpha$  and  $1 - f$  fixed as above is  $\chi^2 = 342.8$  for 284 dof; for an absorbing column  $N_{20} = 39.5 \pm 2.0$  cm $^{-2}$ , and a photon index  $\Gamma = 2.1 \pm 0.1$ . Across the 90% confidence range of  $\alpha$  determined from the disk blackbody model,  $0.56 \leq \alpha \leq 1$ , the range of acceptable power-law indices is  $2.0 \leq \Gamma \leq 2.3$ . The

largest systematic contributions to  $\chi^2$  for this model occur just above the 2 keV Ir-M edge. This is precisely where contributions from pile-up from photons at the peak of the energy distribution (at  $\sim 1.0$ – $1.5$  keV) occurs. Adding a broad Gaussian line to the model significantly improved the fit to  $\chi^2 = 298.0$  for 281 dof. The resulting absorbing column is  $N_{20} = 31.2 \pm 2.0$  cm $^{-2}$ , and the photon index is  $\Gamma = 1.71 \pm 0.09$ . The aperture-corrected model predicted flux in the 0.3–8.0 keV band is  $3.9 \times 10^{-12}$  ergs cm $^{-2}$  s $^{-1}$ , corresponding to a luminosity of  $L = 6.0 \times 10^{39}$  ergs s $^{-1}$ .

An optically thin thermal plasma model can also produce an acceptable fit provided the abundance is kept low to reproduce the observed continuum-dominated spectrum. The best-fit parameter values for X6 are  $kT = 3.5 \pm 0.4$  keV,  $N_{20} = 30.7 \pm 1.8$  cm $^{-2}$ , for  $\chi^2 = 310.0$ , 283 dof, and the metal abundance constrained to 0.03 of the solar value. This model produces few strong spectral lines with the exception of Fe K $\alpha$  at 6.7 keV. Adding a line at this energy to either the disk blackbody or power-law models is not statistically significant.

The results given above are consistent with another test we conducted: The spectrum of X6 was extracted from an annulus with a 1''5 inner radius (compared to the 2'' outer radius used for applying the pile-up model). In this case pile-up is not an issue and a simple absorbed disk blackbody or power-law model is sufficient. The resulting model parameters were consistent with those quoted above, though the formal errors are considerably larger because of the lower number of source photons detected in the extraction region.

#### 4.2.2. X6 Radial Profile

A two-dimensional Gaussian model fitted to the spatial distribution of X-ray events places source X6 at  $9^{\text{h}}55^{\text{m}}32^{\text{s}}.98 \pm 0^{\text{s}}.08$ ,  $+69^{\circ}0'33''.4 \pm 0''.4$  (ignoring the absolute uncertainty in source positions, see § 2 and Table 1). Source X6 is coincident with a large SNR candidate. Wang

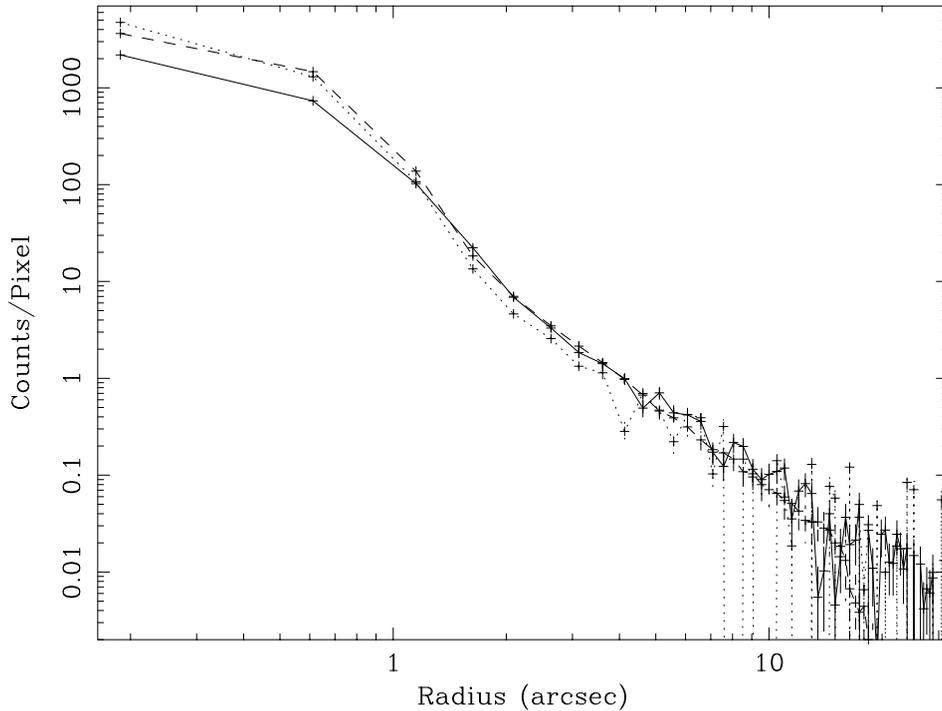


FIG. 4.—Radial profile of source X6 (solid line). X6 is located  $\sim 1'$  off-axis. The profiles of SN 1993J (dotted line;  $\sim 20''$  off-axis) and the 1.5 keV,  $1'$  off-axis, model PSF (dashed line) are shown for comparison. There is no evidence for source extension in the X-ray profile of X6.

(1999) identified several X-ray-bright sources apparently associated with SNRs based on *ROSAT* observations of M101 and concluded that the blast wave energies of these SNRs exceed theoretical predictions of supernova explosions by factors of 30 or greater. In the case of X6, the superb angular resolution of the *Chandra* image can be used to determine the extent of the source on scales much less than the  $\sim 5''$  size of the candidate SNR (No. 22, Table 10, Matonick & Fesen 1997).

Figure 4 displays the radial profile of source X6, along with a model of the radial profile for a point source located at the off-axis position of X6, and the observed radial profile of SN 1993J. The total number of counts in the model PSF and the SN 1993J profile were scaled to 1.6 times the total number of counts detected in the X6 profile. This accounts for the 40% pile-up estimated for source X6. As can be seen, the majority of the pile-up occurs in the innermost two radial bins (with an area of 9 pixels). The profile of SN 1993J is slightly more concentrated than either the model PSF or the X6 profile consistent with its closer proximity to the aimpoint ( $20''$  compared to  $\sim 58''$  for X6). There is no evidence that X6 is an extended source; including in the  $5''$  region occupied by the SNR.

#### 4.2.3. Potential X6 Counterparts

A weak uncataloged radio source visible in the 21 cm map of Bash & Kaufman (1986) is coincident with the *Einstein* High Resolution Imager position of source X6 according to Fabbiano (1988). The source is not seen in a 6 cm VLA image taken on 1999 November 23 above the  $\sim 80 \mu\text{Jy}$   $3\sigma$  limit but is detectable in a 3.6 cm image obtained 1994 December 23 at a flux density of  $\sim 95 \mu\text{Jy}$ , just above the  $3\sigma$  signal-to-noise limit. The radio source extension cannot be reliably measured at this low signal level.

Figure 5 displays an archival *HST* WFPC2 F555W image of the region containing X6 with the X-ray source position identified by a  $1''$  radius circle. An optical source is clearly present within  $\sim 0.2''$  of the X6 location. The observed *HST* magnitudes are  $F336W = 22.8 \pm 0.2$ ,  $F439W = 24.1 \pm 0.3$ ,  $F555W = 24.1 \pm 0.1$ ,  $F675W = 23.9 \pm 0.2$ , and  $F814W = 23.7 \pm 0.5$ . Estimating the color excess from the hydrogen column density obtained from the X-ray spectrum, the optical properties are consistent with an early-type main-sequence star of spectral class O9–B1, though the source is relatively bright in the *R*-band ( $F675W$ ) image, perhaps due to  $H\alpha$  emission. Be stars with circumstellar disks can emit strong  $H\alpha$  under certain circumstances. The equivalent  $H\alpha$  flux is  $\sim (5.4 \pm 0.9) \times 10^{-15}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$  assuming all the *R*-band flux is from this emission line. Matonick & Fesen (1997) report the  $H\alpha$  flux from the SNR candidate to be  $1.1 \times 10^{-14}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$ . The point source can, therefore, contribute as much as one-half of this amount. Note that the point source flux estimate is not contaminated by any underlying extended emission because the source and background extraction regions used in our analysis (§ 3.2) lie wholly within the region occupied by the candidate SNR.

If the X-ray emission is from an accretion disk, then it is possible that some or all of the optical emission is also from an accretion disk instead of from a companion star (or from another object in the field). The color index,  $\xi \equiv B_0 + 2.5 \log F_X$ , where  $B_0$  is the reddening-corrected *B* magnitude and  $F_X$  is the 2–10 keV X-ray flux in  $\mu\text{Jy}$ , was introduced by van Paradijs & McClintock (1995) to quantify the observed relationship between X-ray and optical flux from accretion-powered X-ray binaries. The average value of  $\xi$  for systems in which the secondary star does not contribute significantly to the optical

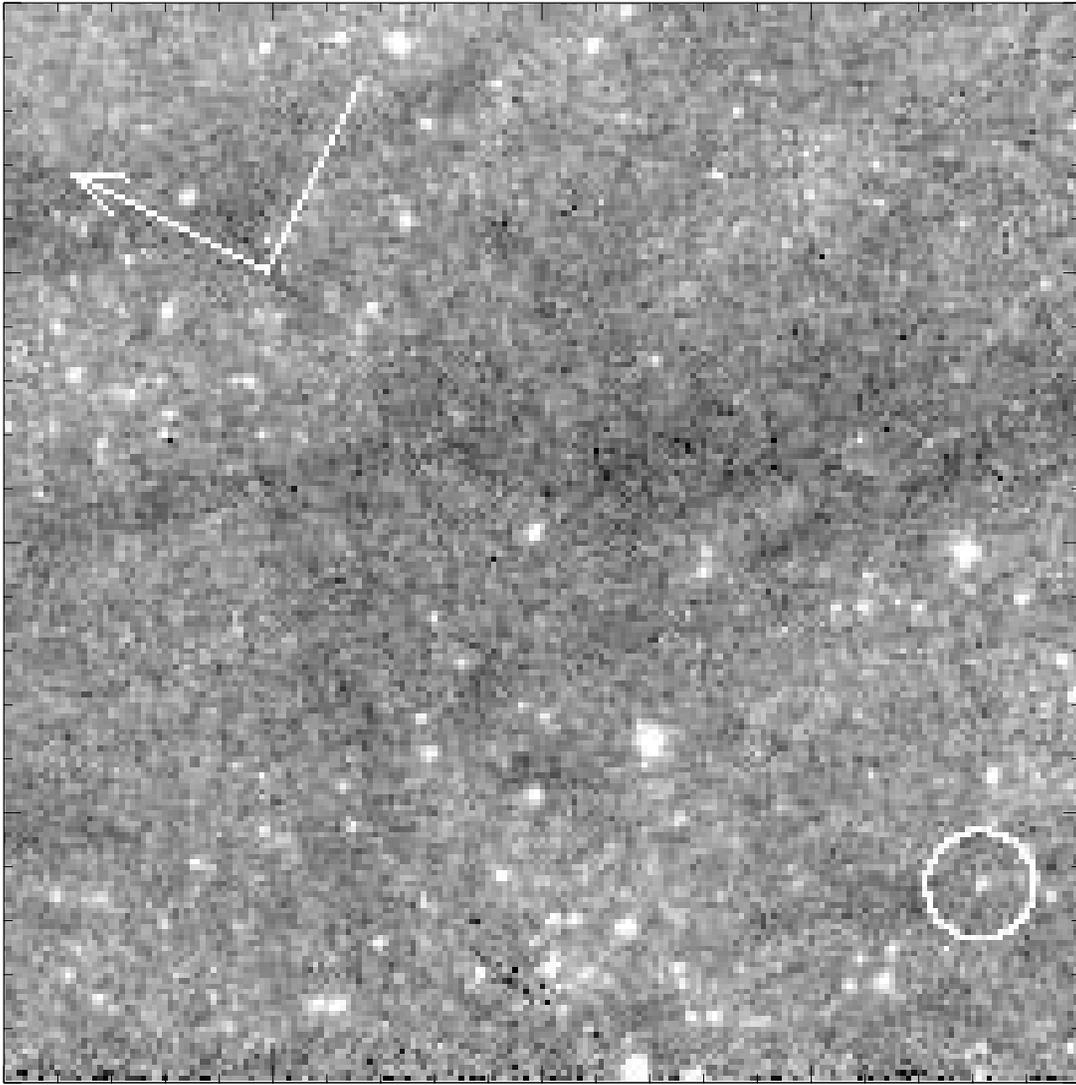


FIG. 5.—*HST*/WFPC2 image of the region surrounding source X6 taken with the F555W filter. The  $1''$  radius circle at the lower left denotes the X-ray position in the *Chandra* data. The arrow indicates the direction of north, and the line segment denotes east. The optical properties of the object at the location of X6 is consistent with a main-sequence star of spectral class O9–B1.

brightness (namely, those with low-mass donor stars) is  $21.8 \pm 1.0$  (errors are 1 standard deviation). This can be compared to X6, where  $\xi \sim 22.5 \pm 1.5$  (where the error includes an uncertainty of 0.15 mag in the color excess). The average colors for these systems are  $(B-V) = -0.09 \pm 0.14$  and  $(U-B) = -0.97 \pm 0.17$  compared to  $(B-V) = -0.1 \pm 0.3$  and  $(U-B) = -1.4 \pm 0.3$  for X6.

The observed X-ray-to-optical flux ratio,  $\sim 900$ , is far too large for typical foreground objects. Normal stars have ratios in the range  $10^{-4}$  to 0.1 (Maccacaro et al. 1988) and cataclysmic variables (CVs) have ratios in the range 0.1 to 10.0 (Bradt & McClintock 1983). The only extragalactic sources with very high ratios of X-ray to optical flux are the BL Lac sources with ratios in the range 10 to 50 (Maccacaro et al. 1988). To produce the ratio observed for X6 requires an optical extinction greater than 4 mag, a possibility excluded by the X-ray-measured hydrogen column density of  $\sim 2 \times 10^{21} \text{ cm}^{-2}$ .

#### 4.2.4. X6 Variability

Tests for source flux variability were applied to counts extracted from both the entire source region and to counts in the inner  $3 \times 3$  pixel region and to the outer source region. There is no evidence of pulsations or other variability in any of these regions. However, periods of higher flux would incur more pile-up. This tends to smooth the light curve by reducing the observed count rate during these high flux periods.

We performed similar analysis of the extensive set of *ROSAT* observations and found no large-scale variability on timescales as short as the *ROSAT* orbital period. Immler & Wang (2001) report a factor of 2 change in the X6 *ROSAT* PSPC count rate over a 6 day period in 1993 November. Our analysis of these data find a modest, maximum  $22\% \pm 7\%$ , change in count rate, but the data are statistically consistent with no variation when compared to SN 1993J. Mizuno (2000) reports that variability of X6 in the

*ASCA* data cannot be assessed because of the unavoidable contribution from the bright nucleus.

#### 4.3. The Galactic Nucleus

The nucleus of M81 has long been an object of study. It is optically classified as a low-ionization nuclear emission line region (LINER) (Ho, Filippenko, & Sargent 1996). The dominant source of energy in LINERs may be mechanical heating by shocks, photoionization by hot stars, or photoionization by a low-luminosity active galactic nucleus (AGN). The nucleus of M81 shows evidence of a low-luminosity AGN including a compact radio core (Bietenholz et al. 2000), broad H $\alpha$  emission (Peimbert & Torres-Peimbert 1981), a UV-bright continuum (Devereux et al. 1997) with broad, AGN-like emission lines (Maoz et al. 1998), and a power-law X-ray continuum (Ishisaki et al. 1996; Pelligrini et al. 2000). These are all consistent with the presence of a  $6 \times 10^7 M_{\odot}$  object, as inferred from dynamical studies (Bower et al. 2000), at the galactic center.

There have been numerous X-ray studies of the nucleus including *Einstein* (Elvis & van Speybroeck 1982), *GINGA* (Ohashi et al. 1992), *BBXRT* (Petre et al. 1993), *ROSAT* (Radecke 1997), *ASCA* (Ishisaki et al. 1996; Iyomoto & Makishima 2001), *BeppoSAX* (Pelligrini et al. 2000), and *XMM-Newton* (Page et al. 2003a, 2003b). A summary of the current and previous X-ray observations of the M81 nucleus is given in Table 4. In addition to a power law with a slope of 1.9, similar to those of luminous Seyfert 1 nuclei (Turner & Pounds 1989; Nandra et al. 1997; Terashima et al. 2002), low-resolution X-ray observations suggest a soft thermal component is present in the nucleus. While both advection-dominated accretion flows (ADAFs) and accretion disk coronae can provide the necessary Comptonizing medium to produce the observed power-law X-ray spectrum, the source of the thermal component remains an outstanding issue. This is also true in other wavebands. The UV continuum is weak relative to X-rays and the “big blue bump” is absent in M81; perhaps a manifestation of a low accretion rate (Ho et al. 1996) or the presence of an ADAF (Quataert et al. 1999).

Though past X-ray observations have been unable to resolve the nucleus from the surrounding diffuse emission and pointlike sources, Tennant et al. (2001) have shown that some  $\sim 10^{39}$  ergs s $^{-1}$ , or a few percent, of the X-ray luminosity in the nuclear region actually originates within a rather

extended ( $\sim 2.5$ ) region of the bulge. A similar conclusion has been reached more recently by Immler & Wang (2001) from analysis of *ROSAT* data and by Page et al. (2003a, 2003b) from *XMM-Newton* RGS spectral analysis.

The high X-ray flux from the nucleus leads to a severe pile-up of events in the ACIS detector, making the point-source spectrum unsuitable for study (although J. Davis has successfully analyzed the nuclear spectrum; J. Davis, 2002, private communication). In this work, the nuclear spectrum was instead extracted from two  $10''$  wide rectangular regions spanning the readout trail and offset  $>30''$  from the nucleus to avoid contamination by events in the wings of the nuclear PSF. The background was extracted from four similar rectangular regions adjacent to the readout trail.

A simple absorbed power-law model provides a statistically acceptable fit to the nuclear spectrum ( $\chi^2 = 114$  for 104 dof; Fig. 6). The resulting power-law fit parameters are listed in Table 4. The addition of a thermal component did not improve the fit significantly ( $\Delta\chi^2 = 0.4$  for one additional parameter with the temperature parameter constrained to  $kT = 0.5$  keV). Detection of Fe K $\alpha$  emission could not be confirmed because of the lack of source counts above  $\sim 5$  keV in the extracted spectrum. This line was previously detected in *Ginga* (Ohashi et al. 1992), *ASCA* (Ishisaki et al. 1996), *BeppoSAX* (Pelligrini et al. 2000), and, recently, *XMM-Newton* PN (R. Soria 2002, private communication) observations of M81.

The 90% upper limit to the thermal model normalization corresponds to a maximum thermal contribution to the nuclear flux of 2.8% or a luminosity in the 0.3–8.0 keV band of  $\sim 9 \times 10^{38}$  ergs s $^{-1}$ . While this is only a small fraction of the nuclear emission, it is comparable to the total luminosity from unresolved emission in the bulge (§ 5). The lack of a significant thermal component in the *Chandra* nuclear spectrum is in contrast to results based on low spatial resolution observations including *ASCA*, *BeppoSAX*, and *XMM-Newton* that find one or more thermal components improve the fit significantly. In fact, it is argued in § 5 that any thermal emission from the nuclear region is consistent with an extrapolation of the emission from the region beyond  $\sim 10''$  from the nucleus and therefore is unrelated to the nucleus.

#### 4.4. Other X-Ray–Bright M81 Sources

In addition to SN 1993J, X6, the nucleus, and the brightest supersoft source (Swartz et al. 2002), there are seven

TABLE 4  
X-RAY HISTORY OF THE M81 NUCLEUS

Date	Obs.	$\Gamma^a$	$N_{\text{H}}^b$	$F^c$	Reference
1979 Apr .....	<i>Einstein</i>	$3.0^{+2.0}_{-1.5}$	$68 \pm 58$	$\sim 0.1$	1
1985 Feb .....	<i>EXOSAT</i>	$2.1 \pm 0.2$	$19 \pm 9$	$2.65 \pm 0.25$	2
1987 May .....	<i>GINGA</i>	$2.2 \pm 0.2$	$60 \pm 30$	$2.4 \pm 0.3$	3
1990 Dec .....	<i>BBXRT</i>	$2.2^{+0.3}_{-0.2}$	$41 \pm 10$	$3.6 \pm 0.3$	4
1991–1994 .....	<i>ROSAT</i>	$2.5 \pm 0.3$	$7.4 \pm 0.4$	1.24	2
1993–1999 .....	<i>ASCA</i>	$1.85 \pm 0.04$	10.0	$3.50 \pm 0.12$	5
1998 Jun .....	<i>SAX</i>	$1.86 \pm 0.03$	$12.0^{+3.6}_{-3.0}$	3.8	6
2000 May .....	<i>Chandra</i>	$1.98 \pm 0.08$	$9.4 \pm 2.0$	$3.25 \pm 0.15$	2
2001 Apr .....	<i>XMM</i>	$1.94 \pm 0.06$	$3.4 \pm 0.8$	$0.93 \pm 0.06$	7

<sup>a</sup> Power-law photon index.

<sup>b</sup> Solar-abundance absorption column, in units of  $10^{20}$  cm $^{-2}$ .

<sup>c</sup> 2–10 keV observed flux, in units of  $10^{-11}$  ergs cm $^{-2}$  s $^{-1}$ .

REFERENCES.—(1) Fabbiano 1988; (2) this work; (3) Ohashi et al. 1992; (4) Petre et al. 1993; (5) Iyomoto & Maikshima 2001; (6) Pellegrini et al. 2000; (7) Page et al. 2003a, 2003b.

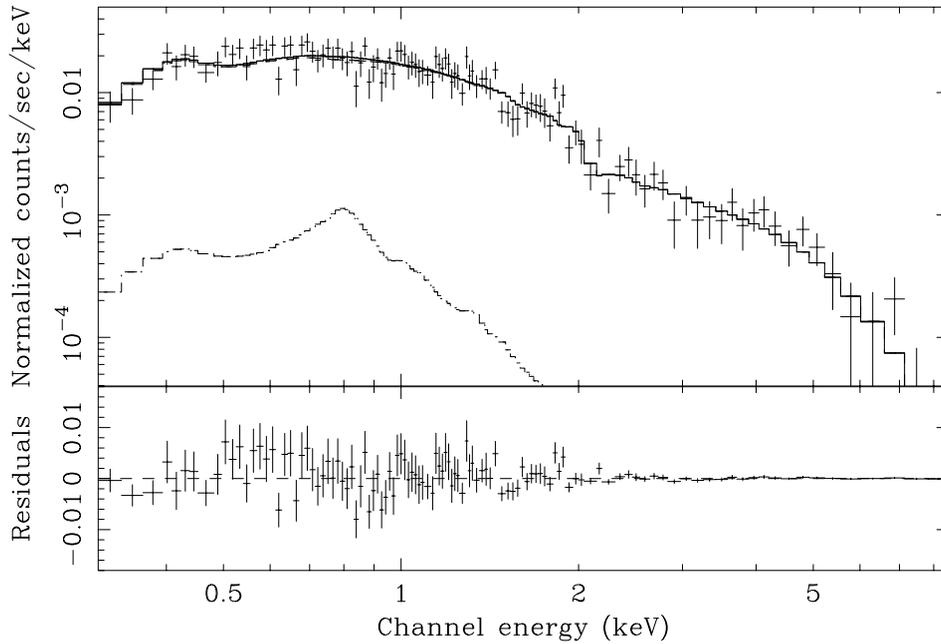


FIG. 6.—Spectrum of the M81 nucleus extracted from the readout trail. Shown are the contributions from a  $\Gamma = 1.98$  power-law (solid line) and a weak thermal component (dot-dashed line). The addition of the thermal component does not improve the fit significantly ( $\Delta\chi^2 = 0.4$  for 1 additional parameter).

X-ray point sources with luminosities exceeding the Eddington limit for a  $1.5 M_{\odot}$  accretor in M81. Four of these are the *Einstein* sources X7, X4, X10, and X3 in order of decreasing brightness. These have all also been detected in the *ROSAT* data (Table 2). In addition, source number 83 was detected by *ROSAT*. The two remaining bright sources are confused with nearby sources in the *ROSAT* and *Einstein* observations: Source number 116 is only  $16''$  from the nucleus, and source number 57 is  $19''$  from (and of comparable luminosity to) X10. Thus, aside from the two confused sources, the brightest sources must be relatively steady sources.

The X-ray spectra of these sources are unremarkable with the exception of source X4 (number 86), which is extremely flat,  $\Gamma = 1.08 \pm 0.13$ , and source number 57, which has a relatively high column density,  $N_{20} = 99.1 \pm 40$ . Our analysis of the *ROSAT* PSPC spectra of these two sources is consistent with these values (though source 57 is confused with source X10, number 52). All seven sources are within the  $D_{25}$  isophote of M81. Three are within the bulge as is the brightest supersoft source (number 132). There are no discernible optical or UV counterparts to any of these seven sources with the exception of source number 146, *Einstein* source X7, which is coincident with globular cluster number 63 of Chandar et al. (2001).

While the majority of these bright sources are persistent sources, two *Chandra* sources of sub-Eddington luminosity are known to have been much more luminous in the past. These are *Chandra* source numbers 67 (*Einstein* source X2) and 82. Ghosh et al. (2001) analyzed source number 82 in detail and noted that both it and X2 are spatially coincident with optically bright objects which may be bright M81 globular clusters. The bright transient source number 82 reached a peak unabsorbed luminosity of  $\sim 7 \times 10^{38}$  ergs  $s^{-1}$  during *ROSAT* observations but was observed at  $1.7 \times 10^{37}$  ergs  $s^{-1}$  in the *Chandra* data (Ghosh et al. 2001). Source X2 is not known to have exceeded  $\sim 2 \times 10^{38}$  ergs  $s^{-1}$ . All *ROSAT* sources in the tabulation of Immler & Wang (2001) falling within the *Chandra* field of view have *Chandra*-detected

counterparts (Table 2). No other bright transients are present in these two tabulations based on a comparison of the *Chandra* count rates derived in this work and the *ROSAT* count rates tabulated by Immler & Wang (2001).

## 5. THE M81 BULGE

The inner Lindblad Resonance, located at an inclination-corrected radius of 4 kpc, separates the bulge and inner disk from the spiral arms and outer disk of M81 (e.g., Kaufman et al. 1989; Reichen et al. 1994). This value is larger than the 2.5 kpc radius adopted by Tennant et al. (2001) in their discussion of bulge and disk emission (and based on the observed X-ray morphology). A 4 kpc radius circle in the plane of the galaxy corresponds to a  $7'.64 \times 3'.94$  ellipse on the plane of the sky with major axis oriented at PA  $149^\circ$ .

The *Chandra* image (Tennant et al. 2001; § 6) shows the bulge X-ray sources concentrated toward the galactic center and excess or unresolved X-ray emission extending away from the nucleus. Analysis of this emission is made difficult by the bright nucleus. While the high angular resolution of the *Chandra* mirrors concentrates most of the nuclear X-rays into the central few pixels, the small fraction incident in the wings of the PSF accounts for a large percentage of the total number of X-rays detected at larger radii.

In this section, the spatial distribution of the bulge X-ray emission is analyzed and compared to the distribution observed in other wavebands. The spectral properties are then assessed to determine the possible contributions from different sources of X-ray emission as a function of position within the bulge.

Of particular interest is the central  $\sim 30''$ – $50''$  inner region or core of the galaxy. Unlike the smooth distribution of optical light, there is filamentary  $H\alpha$  emission (Devereux et al. 1995) and excess UV emission (Hill et al. 1992; Reichen et al. 1994) in the core. The origin of this emission is uncertain. It has been attributed to recent star formation activity (Devereux et al. 1995) but more likely originates from hot

evolved post-AGB stars (O’Connell et al. 1992; Devereux et al. 1995). High-resolution *HST* images rule out massive OB stars as a source of ionization, but ionization by shocks originating from nuclear activity remains a viable alternative (Devereux et al. 1997), a conclusion also reached by Greenwalt et al. (1998).

## 5.1. Spatial Distribution

### 5.1.1. Broadband X-Ray Surface Brightness

The unresolved X-ray surface brightness is obtained by removing the detected sources and the nuclear readout trail from the image. The radial profile of this emission is shown in Figure 7. The profile asymptotically approaches the background level of  $0.04 \text{ counts pixel}^{-1}$  at a radius of  $\sim 2'$  ( $\sim 2 \text{ kpc}$ ). Also shown is the estimated contribution from the nuclear point source and the resulting profile with the nuclear contribution subtracted. The contribution from the nucleus was estimated using a model PSF appropriate for the observed off-axis location of the nucleus and for 1.5 keV photon energies. This energy is above the  $\sim 0.8 \text{ keV}$  peak of the observed spectrum of the nucleus (§ 4.3) but is representative and avoids interpolation between PSF models at different discrete energies. The radial profiles show a strong nuclear contribution within the central  $\sim 30''$  but which falls much more steeply than the observed excess at larger radii. Toward the center of the galaxy, the estimated contribution from the nucleus exceeds the observed surface brightness due to pile-up of nuclear photons. Analysis is therefore confined to the region beyond  $\sim 10''$  from the nucleus.

The excess X-ray emission (with the estimated nuclear PSF contribution subtracted) was examined to determine the shape of the emission and to compare to profiles at other wavelengths. Both the bulge and the underlying galactic

disk can contribute to the excess X-ray surface brightness. If the excess is confined to the disk, then its distribution should appear elongated in an elliptical pattern consistent with the known inclination of M81. If the emission is from the bulge, then its distribution on the plane of the sky should appear azimuthally symmetric about the nucleus.

Azimuthal profiles extracted over a range of spatial scales show no significant departures from azimuthal symmetry with one exception: There is a slight ( $\sim 30\%$ ) increase in X-ray surface brightness in a region located  $30''$  to  $45''$  to the northeast of the nucleus. This is also the location of a non-thermal highly polarized radio arc that may be a small-scale nuclear radio lobe (Kaufman et al. 1996). A two-dimensional Gaussian model fitted to the excess X-ray surface brightness shows a slight elongation along PA  $153^\circ \pm 2^\circ.4$  and an eccentricity of 0.56. This is much less than expected from the galaxy disk inclination (eccentricity 0.86) and slightly smaller than the  $\sim 0.66$  measured in the inner 0.1–1 kpc from *UBVR* isophotes (Tenjes, Haud, & Einasto 1998). Qualitatively, this suggests that the excess X-ray surface brightness is emitted predominantly from the spherical bulge but that the disk also contributes.

A more quantitative estimate of the disk and bulge contributions can be made by fitting the radial profile of the excess X-ray surface brightness with a generalized exponential of the form  $\Sigma(r) = \Sigma_0 e^{-(r/h)^{1/n}}$  (e.g., de Jong 1996). The PSF-corrected and background-subtracted X-ray surface brightness profile is shown in Figure 8 along with the best-fit curves for  $n \equiv 1, 2,$  and  $4$ . None of the fits are statistically acceptable, with  $\chi^2$  values ranging from 160.4 to 203.1 for 116 dof. Allowing  $n$  to vary improved the  $\chi^2$  value only slightly to 154.6 for the best-fit value  $n = 1.56 \pm 0.30$ . This value is intermediate between an exponential disk ( $n = 1$ ) and a de Vaucouleurs bulge ( $n = 4$  or  $R^{1/4}$  law) profile. Fitting only the region beyond  $1'$  of the nucleus reduced  $\chi^2$  sub-

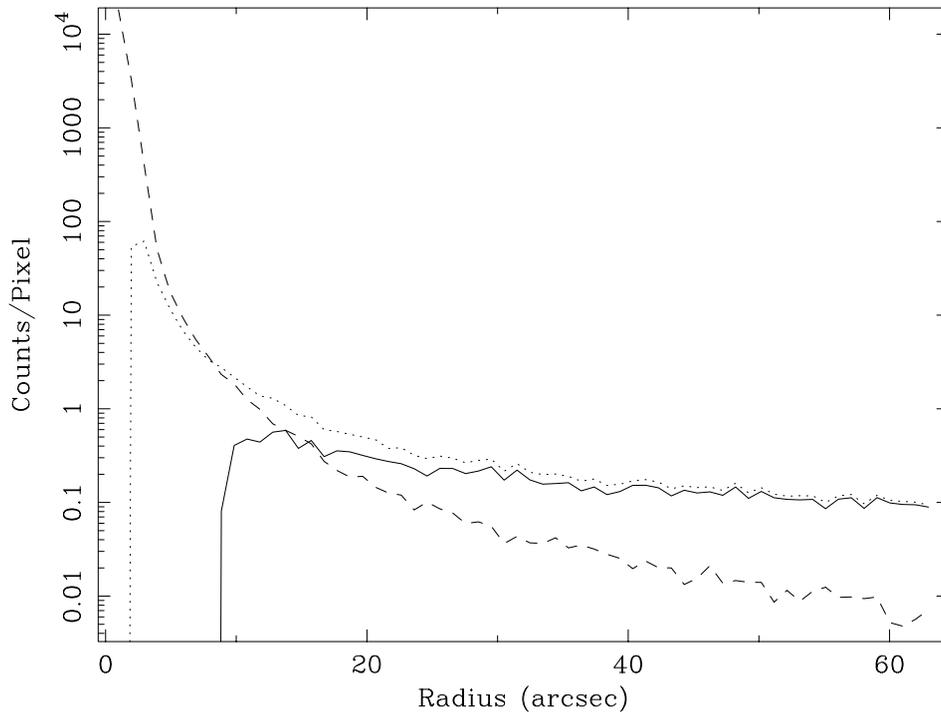


FIG. 7.—Curves tracing the radial profile of the observed X-ray surface brightness (*dotted line*), the model point spread function of the nucleus (*dashed line*), and the difference of the two (*solid line*). Errors have been omitted for clarity. The background level is  $\sim 0.04 \text{ counts s}^{-1}$ .

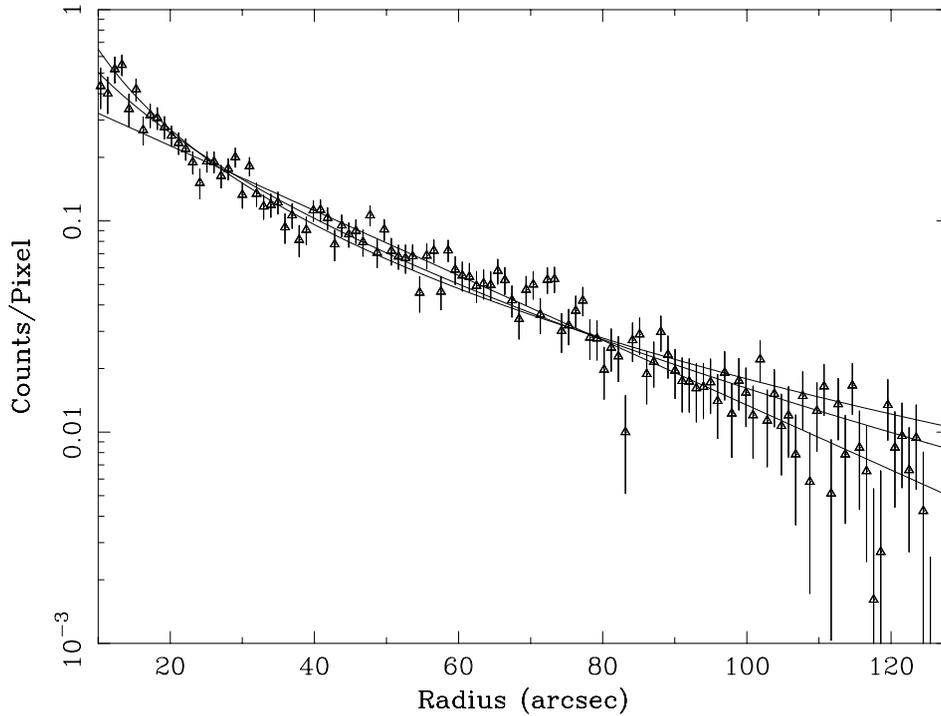


FIG. 8.—Background-subtracted and PSF-corrected excess X-ray surface brightness radial profile. Curves represent best fits using a generalized exponential function of the form  $\Sigma(r) = \Sigma_0 e^{-(r/h)^n}$  with  $n = 1, 2,$  and  $4$ . (Curvature increases with increasing  $n$ ; the exponential,  $n = 1$ , is the straight line).

stantially for  $n = 1$  (65.4 for 65 dof) and results in a best-fit value of  $n = 1.1 \pm 0.1$  ( $\chi^2 = 65.3$  for 64 dof). The X-ray emission at large radii therefore generally follows the exponential disk profile typically seen in optical light from spiral galaxies but steepens to a bulge-dominated profile near the nucleus.

Figure 9 compares the X-ray surface brightness profile to those observed at other wavelengths. The X-ray surface brightness follows the optical (courtesy P. Tenjes 2002, private communication) and near-UV<sup>8</sup> (centered at 2490 Å) light from old bulge stars out to  $\sim 80''$  but declines more rapidly at larger radii. In contrast, the far-UV (1520 Å) profile falls rapidly to the background level beyond  $50''$  of the nucleus (Hill et al. 1992). The resulting UV color gradient has been interpreted as a gradient in metal abundance in the inner  $\sim 50''$  (O’Connell et al. 1992). There is no indication of a similar enhancement in the X-ray data, but, again, the morphology within the inner  $\sim 10''$  cannot be determined owing to the X-ray brilliance of the nucleus.

#### 5.1.2. Resolved Sources

The radial distribution of the observed counts (excluding the nucleus) in the resolved X-ray population superposed on the excess X-ray surface brightness profile is displayed in Figure 10. The profiles are remarkably similar with the exception of the single high bin due to a single bright (super-soft) source (number 132) located  $\sim 50''$  from the nucleus.

The radial distribution of the 53 resolved bulge X-ray sources (per unit area) is flatter than the surface brightness profile. There is, however, a bias in the source detection efficiency in the center of the galaxy where the excess X-ray

surface brightness is highest and acts as an increased background for source detection. This naturally causes a flattening in the resolved source number distribution.

#### 5.2. X-Ray Spectrum of the Unresolved Component

The unresolved X-ray emission may be composed of unresolved point sources and of diffuse, shock-heated, gas. The spectrum of the unresolved X-ray emission was extracted from  $15''$  wide annuli centered on the nucleus with the inner radius of the first annulus equal to  $10''$ . At least three spectral components are included in spectral fits for each annulus: a nuclear contribution, a power law, and a thermal component.

The contribution from the wings of the PSF of the nucleus can be estimated by scaling the spectrum obtained from the nuclear readout trail (§ 4.3) by the fraction of the PSF falling within the chosen annulus. However, this scaling preserves the shape of the nuclear spectrum and does not account for the spectral flattening that occurs because of the energy dependence of the PSF. The deep calibration observation of the point source LMC X-1 (obsid 1422) was used to model this effect. The readout trail image of LMC X-1 was extracted along with spectra from various annuli surrounding the source. The channel-by-channel ratio of these spectra shows a linear rise with energy reflecting the PSF energy dependence. Applying this result to the nucleus of M81 modifies the power-law form of the readout-trail spectrum to a function of the form  $E^{-\Gamma}(aE + b)$  with the constants  $a$  and  $b$  dependent on the annular region under study and the power-law index  $\Gamma$  determined by the shape of the readout trail spectrum (4.3). Subsequently, all parameters for the nuclear contribution to the unresolved emission are held constant while fitting the latter spectra.

<sup>8</sup> From archival Ultraviolet Imaging Telescope data available from <http://archive.stsci.edu/uit/index.html>.

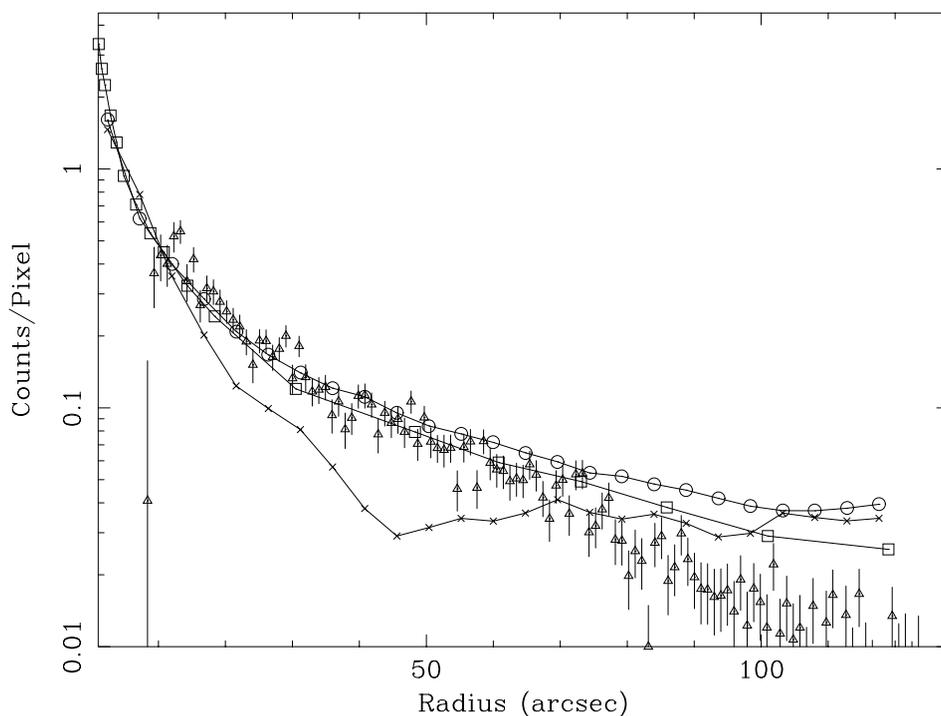


FIG. 9.—Background-subtracted and PSF-corrected excess X-ray surface brightness radial profile (*triangles*) with optical (*squares*), near-UV (*circles*), and far-UV (*crosses*) profiles. Non-X-ray profiles have been scaled vertically to match the X-ray data at a radius of  $10''$  for comparison.

The contribution from unresolved sources is assumed to have the same shape as that of the resolved sources but with the model normalization left as a free parameter. The spectra of the resolved bulge sources, with the exception of the

nucleus and the bright supersoft source, were added to obtain the total bulge source spectrum and then fitted to an absorbed power law. The resulting column density is  $N_{20} = 7.7$  and the photon index is  $\Gamma = 1.6$  ( $\chi^2 = 156.6$  for

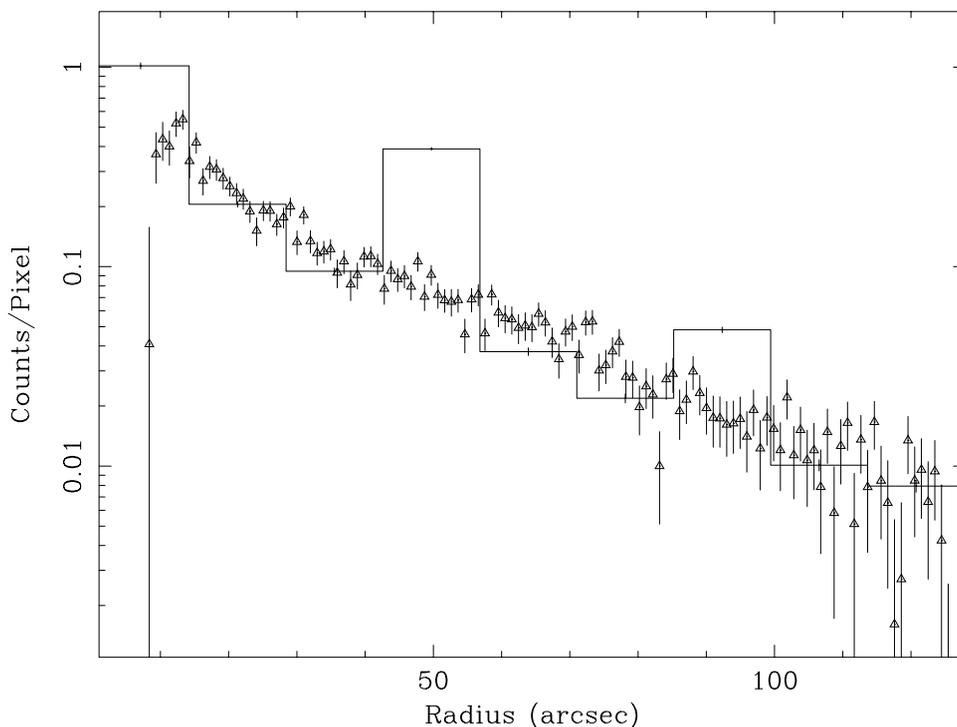


FIG. 10.—Background-subtracted and PSF-corrected excess X-ray surface brightness radial profile (*triangles*) with histogram distribution of X-ray counts detected in resolved X-ray sources (in units of  $c \text{ kpc}^{-2}$ ) overplotted. Profile of resolved source counts has been scaled vertically by  $2.5 \times 10^{-4}$ . The high bin at  $50''$  is due mostly to a single source contributing  $\sim 4000$  X-ray counts.

176 dof). This slope is typical of individual intermediate-brightness sources for which reliable spectral fits could be made (§ 3.3). The total flux is  $9.2 \times 10^{-13}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$ , corresponding to a luminosity of  $1.43 \times 10^{39}$  ergs  $\text{s}^{-1}$  ( $1.64 \times 10^{39}$  ergs  $\text{s}^{-1}$  unabsorbed).

The third component is assumed to be thermal because, when the data are fitted with only the first two components, the bulk of the residual lies at low energies suggestive of a thermal contribution. Models with additional power-law or thermal components were also tested. These components might represent a contribution from weak unresolved sources dissimilar in spectral shape to the resolved sources. None of these added components improved the fit statistic significantly.

A typical spectrum and best-fit model components are displayed in Figure 11. For this annulus, the hard X-ray flux above  $\sim 1.5$  keV is dominated by the nuclear contribution but the thermal and power-law contributions are clearly present.

Figure 12 shows that the temperature profile of the thermal component decreases with distance from the nucleus ( $\langle kT \rangle = 0.38 \pm 0.07$  keV within  $60''$  radius and  $\langle kT \rangle = 0.26 \pm 0.05$  keV between  $60''$  and  $120''$ ,  $\chi^2 = 7.2$  for 5 dof) and that the absorbing column density increases away from the nucleus (from  $N_{20} = 9.1 \pm 2.6$  to  $21.2 \pm 5.3$  on the same ranges, respectively,  $\chi^2 = 13.2$  for 5 dof). Assuming a homogeneous distribution of hot gas is responsible for the thermal emission, its density and mass can be estimated based on the shape of the X-ray emitting region discussed above, namely a spherical bulge in the inner  $\sim 1$  kpc surrounded by a region dominated by disk emission. The spectral fit parameters imply the number density of the gas is  $n_e \sim 0.01$   $\text{cm}^{-3}$  but rises to  $n_e \sim 0.07$   $\text{cm}^{-3}$  in the innermost annulus and that the total mass of hot gas within the volume

extending  $\sim 2'$  from the nucleus is  $\sim 7 \times 10^6 M_\odot$ . This is a crude estimate because the thickness of the disk is unknown and was taken to be 1 kpc or roughly the thickness of the Galactic disk. The derived mass is a small fraction of the total mass of the bulge,  $\sim 3 \times 10^{10} M_\odot$  (Tenjes et al. 1998). The total thermal energy in the hot gas is  $\sim 7 \times 10^{54}$  ergs or about 0.3% of the kinetic energy in bulge stellar motion (see Tenjes et al. 1998).

Page et al. (2003a, 2003b) argued that the unresolved emission is from collisionally excited, optically thin plasmas based the RGS data obtained by *XMM-Newton*. A model consisting of three mekal components (with  $kT = 0.18 \pm 0.04$ ,  $0.64 \pm 0.04$ , and  $1.7 \pm 0.2$  keV, respectively) and an absorbed power law (with  $\Gamma \approx 1.95$ , representing the nuclear contribution) provides a good fit to the RGS data. From the ratio of the forbidden line to the intercombination lines in the O VII triplets they rule out the alternative photo-ionization model at the 95% confidence level. The ratio of the resonance line to the other lines in the O VII triplet also put an upper limit of  $10^9$   $\text{cm}^{-3}$  to the electron-number density of the line emitting gas. This result together with the luminosity of diffuse gas inferred from the *Chandra* data implies that the gas is not uniformly distributed and it fills only a small fraction of the available volume.

Figure 13 displays the individual contributions to the X-ray luminosity of the unresolved excess emission as a function of the distance from the center of the galaxy. Both the thermal and power-law contributions are relatively flat compared to the nuclear contribution whose spatial dependence is dictated by the shape of the PSF. Also shown in Figure 13 is the possible contribution from thermal emission at the center of the galaxy deduced from analysis of the nuclear readout trail spectrum of § 4.3. This emission is consistent with an extrapolation of the thermal and/or power-law

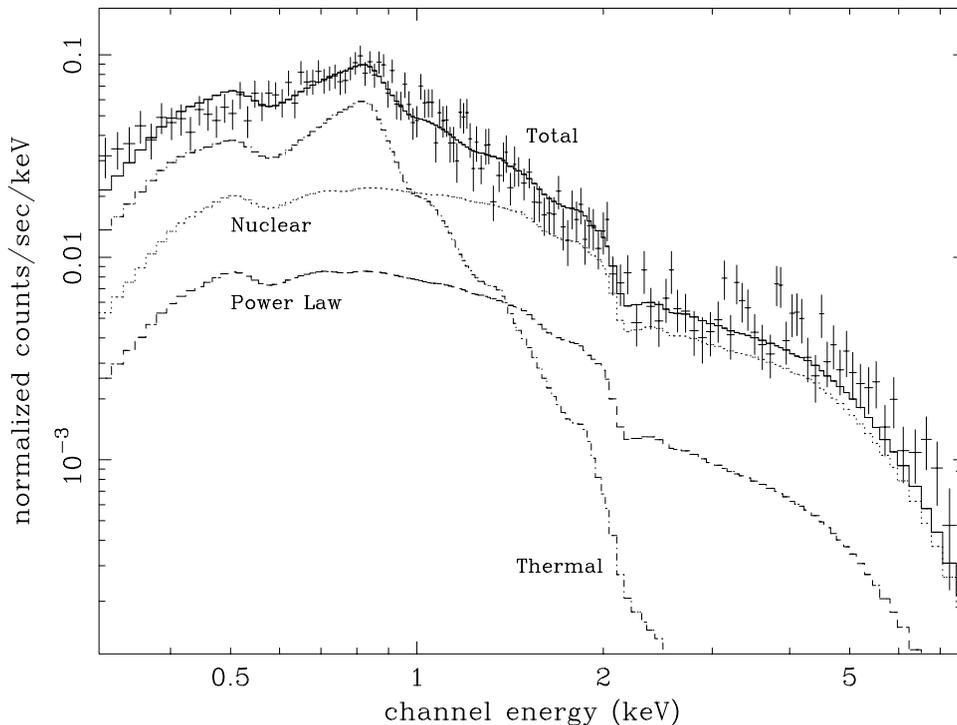


FIG. 11.—Spectrum of the unresolved emission from an annulus spanning 10 to  $30''$  radius from the center of M81. Shown are the contributions from the nucleus, a power law representing unresolved point sources, and a thermal component.

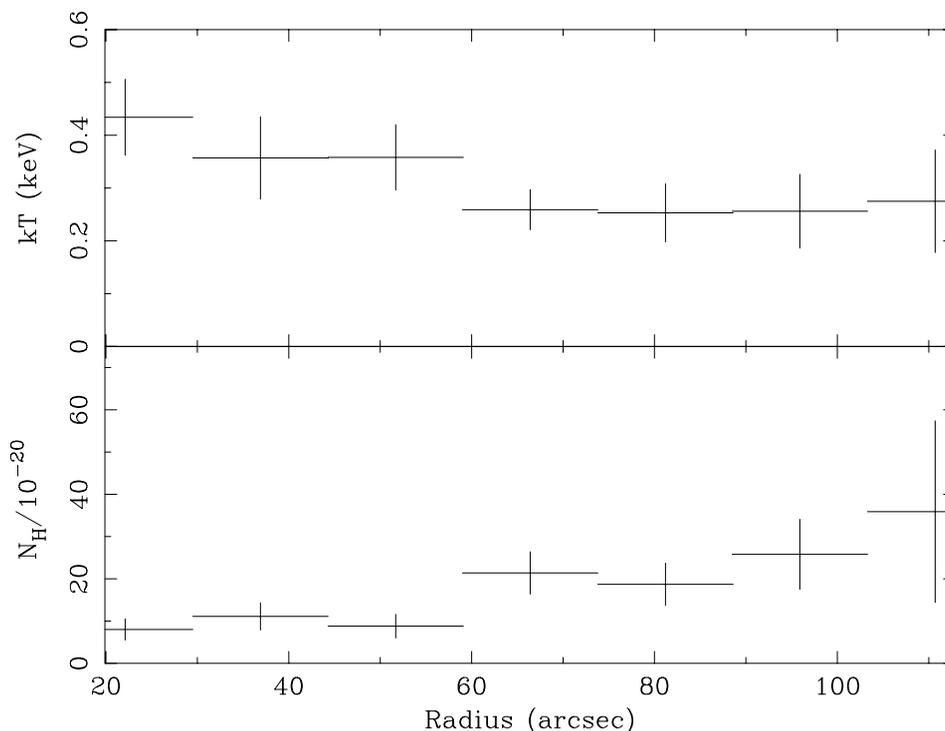


FIG. 12.—Radial variation of the best-fit temperature (*top*) and column density (*bottom*) for the thermal contribution to the unresolved emission from the bulge.

emission from the bulge and therefore is not necessarily intrinsic to the active nucleus.

The total absorbed luminosity in the power-law component is  $5.8 \times 10^{38}$  ergs  $s^{-1}$  and  $4.2 \times 10^{38}$  ergs  $s^{-1}$  in the

thermal component. The total is less than the  $1.6 \times 10^{39}$  ergs  $s^{-1}$  emitted by the discrete bulge sources.

The expected contribution of unresolved discrete sources to the unresolved emission can be estimated by extrapolat-

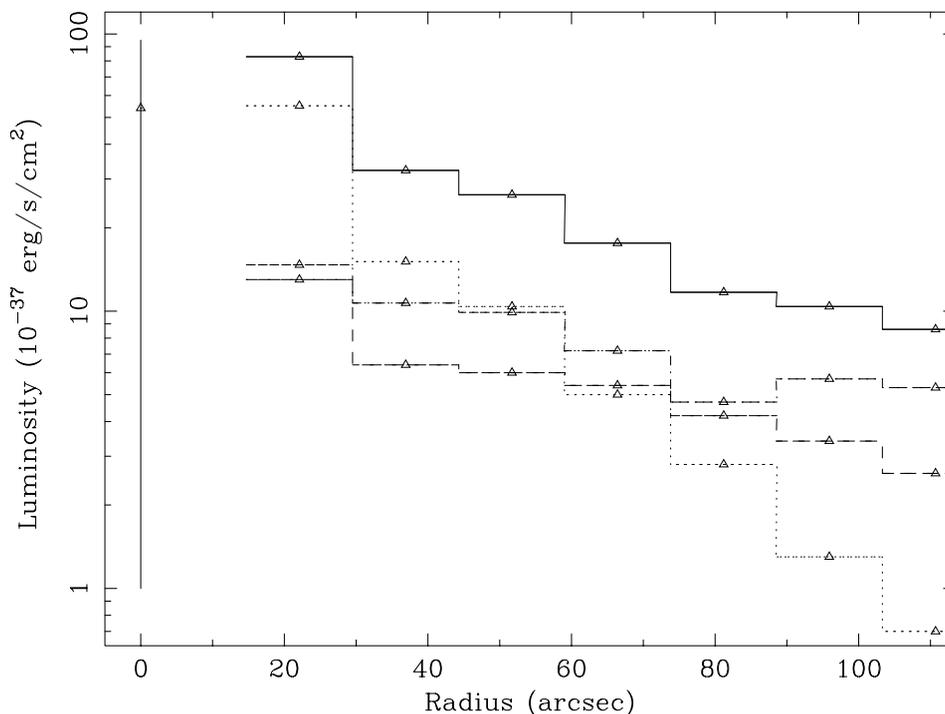


FIG. 13.—Radial dependence of the X-ray luminosity of the unresolved emission from the bulge. Shown are the contributions from thermal (*dashed line*), power-law (*dot-dashed line*), and nuclear PSF (*dotted line*) model components. The solid line represents the total luminosity. Also shown is the estimated thermal emission component at the nucleus obtained by adding a thermal model to the model of the spectrum extracted from the nuclear readout trail (§ 4.3).

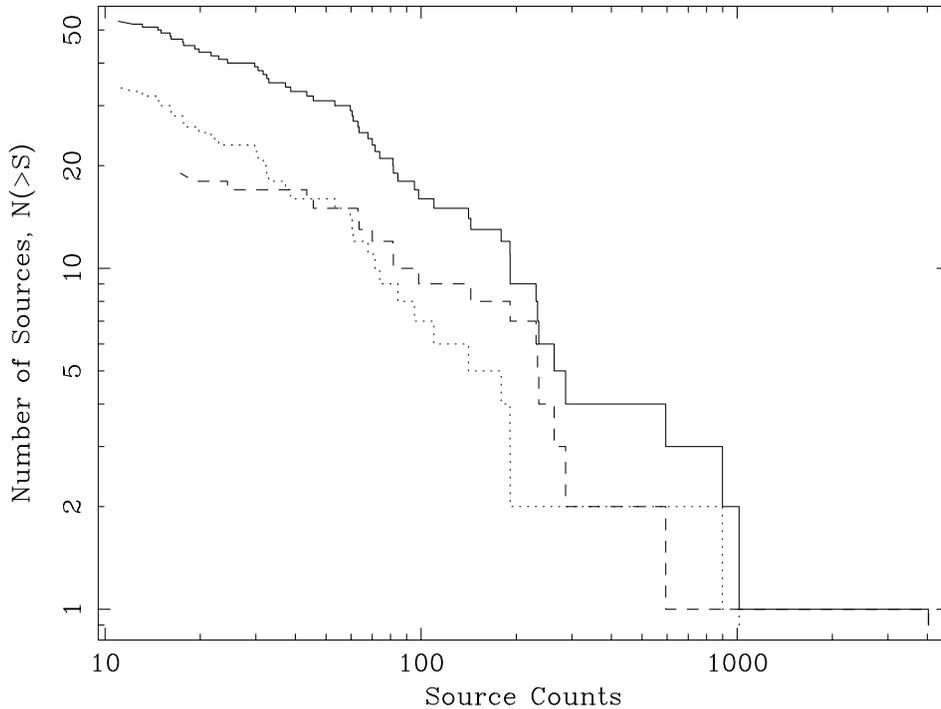


Fig. 14.—Luminosity function for bulge sources (*solid line*). Also shown are the luminosity functions for sources lying within  $1'$  of the nucleus (*dashed line*) and outside (*dotted line*) this radius. Note the lack of weak detected sources in the region near the nucleus due to the high contribution from the nucleus and from the X-ray excess to the source background in this region. The break in the luminosity function at  $\sim 200$  counts corresponds to a luminosity of  $\sim 4 \times 10^{37}$  ergs  $s^{-1}$ .

ing the observed luminosity function of the resolved bulge sources to lower luminosity. The bulge luminosity function is displayed in Figure 14. Also shown are the luminosity functions of the subsets of bulge sources within  $1'$  and beyond  $1'$  of the nucleus. The only systematic differences between the three functions is a flattening of the distribution at low luminosities for sources near the nucleus. This is caused by the loss of sensitivity in this region due to the large contribution of the nucleus to the underlying background. Tennant et al. (2001) pointed out the break in the background-subtracted bulge luminosity function at  $\sim 4 \times 10^{37}$  ergs  $s^{-1}$  ( $\sim 200$  counts). The luminosity function shown here includes 13 more X-ray sources because of the larger ellipse used to define the bulge and is not corrected for background sources. Nevertheless, the break can still be seen. Another change in slope can be envisioned at about 60 counts. This change caused by the loss of sensitivity near the center of the bulge. The luminosity function is a power law,  $N(> C) = (194.1 \pm 12)C^{-0.50 \pm 0.02}$  between 13 and 200 counts and  $N(> C) = (135.6 \pm 5.0)C^{-0.37 \pm 0.01}$  between 13 and 60 counts. Extrapolating these two functions to lower luminosities implies unresolved sources of the type contributing to the resolved-source luminosity function account for only about 4% to 8% of the excess X-ray counts or an equivalent fraction of the luminosity (assuming the spectral shape is preserved).

In summary, the spectrum of the unresolved emission probably has contributions from weak, unresolved sources and from diffuse hot gas. While spectral models show roughly equal contributions from both these components, extrapolation of the resolved-source luminosity function predicts only a small contribution from unresolved discrete sources. Perhaps another, distinct, population of weaker

sources is present and contributes substantially to the unresolved emission. These sources must be quite weak (and hence numerous) as no such population has been resolved in observations of the nearby galaxy M31 to a limiting luminosity of  $\sim 6 \times 10^{35}$  ergs  $s^{-1}$  (Shirey et al. 2001). The thermal component needed to fit the observed excess X-ray spectrum may also be from a collection of weak sources or from truly diffuse gas at  $kT \sim 0.4$  keV. The mass and thermal energy content of any X-ray-emitting gas is small compared to the total mass and energy confined in the bulge. Unlike the distribution of far-UV light, both the unresolved emission and the resolved bulge point-source population trace the optical profile from old bulge stars and are confined by the same gravitational potential. In particular, there is no evidence of enhanced activity in the core such as heating by shocks as may explain the wispy  $H\alpha$  emission (Devereux et al. 1995, 1997).

## 6. THE M81 DISK AND SPIRAL ARMS

In contrast to the bulge, there is no measurable excess X-ray emission in the disk imaged by *Chandra*. In particular, there is no (unresolved) X-ray signature of the spiral arms which are seen clearly at other wavelengths and in X-rays in other galaxies such as M83 (Soria & Wu 2002).

### 6.1. Spatial Distribution and Luminosity Function

The spiral arms are perhaps most clearly seen in UV images (Fig. 15; see also, e.g., Reichen et al. 1994 and Hill et al. 1995) where the population of young stars trace the principal features of the spiral arms. The UV provides a high contrast by not sampling the underlying disk component

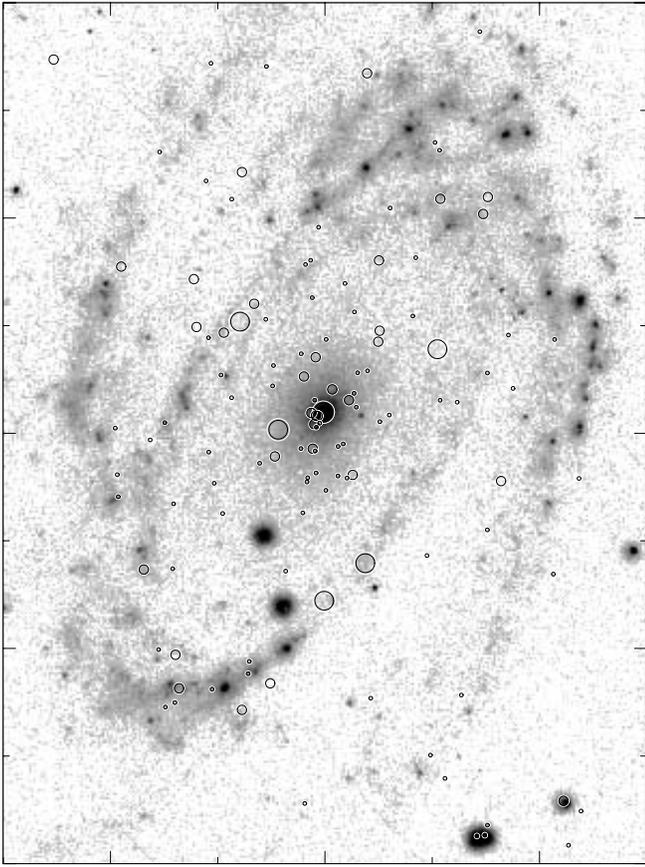


FIG. 15.—Distribution of resolved X-ray sources (*circles*) superimposed on an Ultraviolet Imaging Telescope near-UV image (2490 Å; Hill et al. 1992) of M81. Sources with  $>1000$  source counts are marked with  $10''$  radius circles, those with between 100 and 1000 source counts are marked with  $5''$  radius circles, and those with  $<100$  counts are marked with  $2''$  radius circles.

that is clearly seen in optical light. The archival near-UV image obtained by the Ultraviolet Imaging Telescope, with approximately  $3''$  resolution, was used to define the locations of the spiral arms. Distances between X-ray source positions and the nearest spiral arm was measured. Sources within the  $7/64$  major-axis ellipse defining the bulge/disk interface (§ 5) were excluded, as were those sources exterior to the  $D_{25}$  isophote at  $26.9'$ . Source distances from spiral arms are displayed in Figure 16 against the number of detected X-ray counts. Average distances in three luminosity ranges are also shown. Clearly, the average distance to a spiral arm decreases as the source luminosity increases.

The spatial dependence of the luminosity function for the disk sample is shown in Figure 17. The sample of 72 X-ray sources located interior to the  $D_{25}$  isophote and exterior to the bulge/disk interface was binned into three groups with an equal number of sources in each group corresponding to sources within  $0.30$  kpc of a spiral arm, those  $0.30$ – $0.75$  kpc, and those located  $>0.75$  kpc from spiral arms. Note the strong dependence of the shape of the luminosity function on distance from spiral arms exhibited in Figure 17. Sources located near spiral arms are expected to be associated with the young population of stars recently formed following passage through the density wave, while those further from the spiral arms should be related to a relatively

older population. Thus, the observed X-ray luminosity functions for these populations suggests the younger population contains brighter objects and exhibits a luminosity function with a constant power-law index [ $N(> C) = (75.7 \pm 5.9)C^{-0.48 \pm 0.03}$ ]. Those further from the spiral arms, in contrast, are dominated by weaker sources and their luminosity functions steepen above  $\sim 250$  and  $\sim 100$  counts, respectively (luminosities  $\sim 6 \times 10^{37}$  ergs  $s^{-1}$  and  $\sim 2.4 \times 10^{37}$  ergs  $s^{-1}$ ). A power law fitted to the full data range for sources between  $0.30$  and  $0.75$  kpc gives  $N(> C) = (100.3 \pm 10.8)C^{-0.54 \pm 0.03}$  and for those furthest from the spiral arms,  $N(> C) = (127.1 \pm 16.6)C^{-0.69 \pm 0.04}$ .

## 6.2. X-Ray Spectra

The spectra of the 44 resolved disk sources imaged on device S3, with the exception of SN 1993J and source X6, were added to obtain a representative disk source spectrum to compare to the bulge source spectrum. An absorbed power law with the addition of a thermal component was an improvement over an absorbed power law alone ( $\Delta\chi^2 = 33$  for three additional parameters). The resulting column density is  $N_{20} = 8.1$ , the photon index is  $\Gamma = 1.4$ , and the thermal component temperature and abundance are  $kT = 0.22$  keV and  $Z = 0.2Z_{\odot}$  ( $\chi^2 = 193$  for 172 dof). The thermal component accounts for  $\sim 3\%$  of the total  $0.3$ – $8.0$  keV flux. The power-law slope is flatter than typical of individual sources for which reliable spectral fits could be made ( $\Gamma = 1.5$ , § 3.3) and of the composite spectrum of the resolved bulge sources ( $\Gamma = 1.6$ ). The bulge spectrum also did not require a thermal component. The need for a thermal component suggests some of the weaker resolved disk sources may be X-ray-bright SNRs undetected in radio or in the survey of Matonick & Fesen (1997). Alternatively, a thermal contribution from black hole binaries in high soft states cannot be discounted. On the other hand, the thermal component contributes to the spectrum only at Fe L and at lower energies. A large range of column densities among the individual sources could also mimic this effect.

## 7. DISCUSSION

### 7.1. The Discrete X-Ray Source Population

The X-ray spectra of the brightest sources in the M81 field are predominantly moderately absorbed power laws with photon index  $\Gamma \sim 1.5$ . A similar spectral shape reproduces the combined bulge resolved-source spectrum, while the combined disk source spectrum (for sources on S3) requires an additional weak thermal component. A power law is indicative of accreting X-ray binaries (XRBs), and a large population of bright power-law sources is consistent with surveys of our Galaxy and the Local Group, where the bright X-ray source population is dominated by low-mass XRBs (e.g., Grimm et al. 2001).

The scarcity of X-ray sources detected in the radio, or correlated with optically selected SNRs, or exhibiting a strong thermal X-ray spectrum implies an insignificant number of the bright X-ray sources in M81 are SNRs. Supernova remnants are common in the Magellanic Clouds and in the solar neighborhood but are relatively less luminous and short-lived compared to typical XRBs. Perhaps some of the weaker disk sources are SNRs and account for

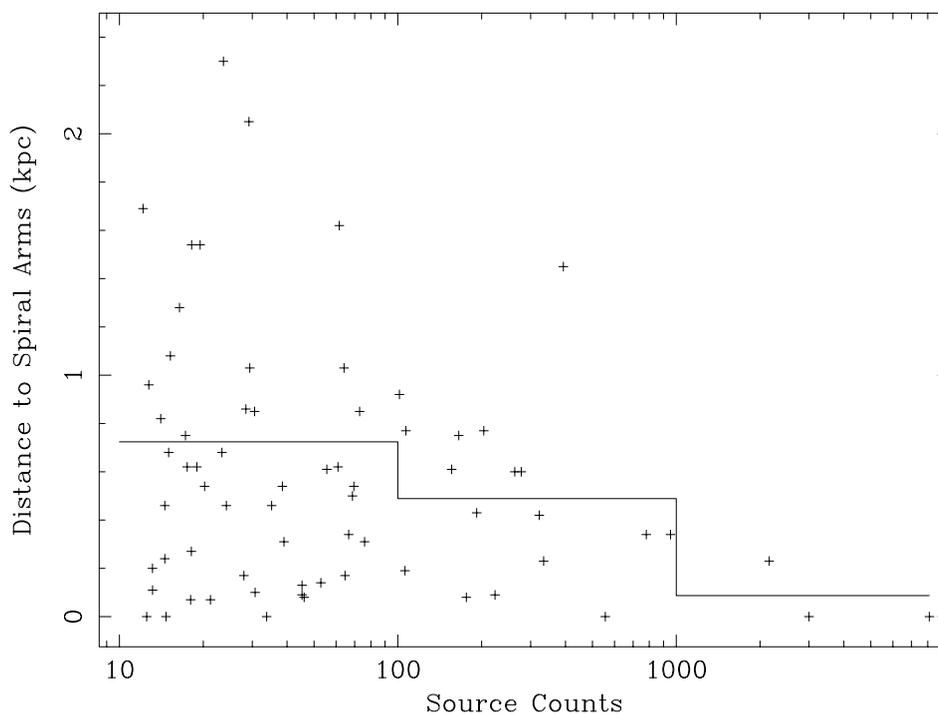


FIG. 16.—Distribution of resolved X-ray sources in the disk. Shown is the distance from the nearest spiral arm against the (background-corrected) source counts. The line shows the average distance to spiral arms for sources in the 10–100, 100–1000, and >1000 count ranges (100 counts corresponds to an unabsorbed luminosity of  $\sim 2.4 \times 10^{37}$  ergs  $s^{-1}$ ).

the thermal emission present in the combined disk source spectrum. Multiwavelength observations of optically identified extragalactic SNRs have revealed that these sources are typically very weak X-ray and radio emitters (e.g., Pannuti et al. 2000; Lacey & Duric 2001; Pannuti et al. 2002).

Four X-ray sources are coincident with known M81 globular clusters. Three other X-ray sources are coincident with optically bright objects with colors consistent with globular clusters and two other X-ray sources have candidate optical counterparts that appear extended in *HST* images. Approx-

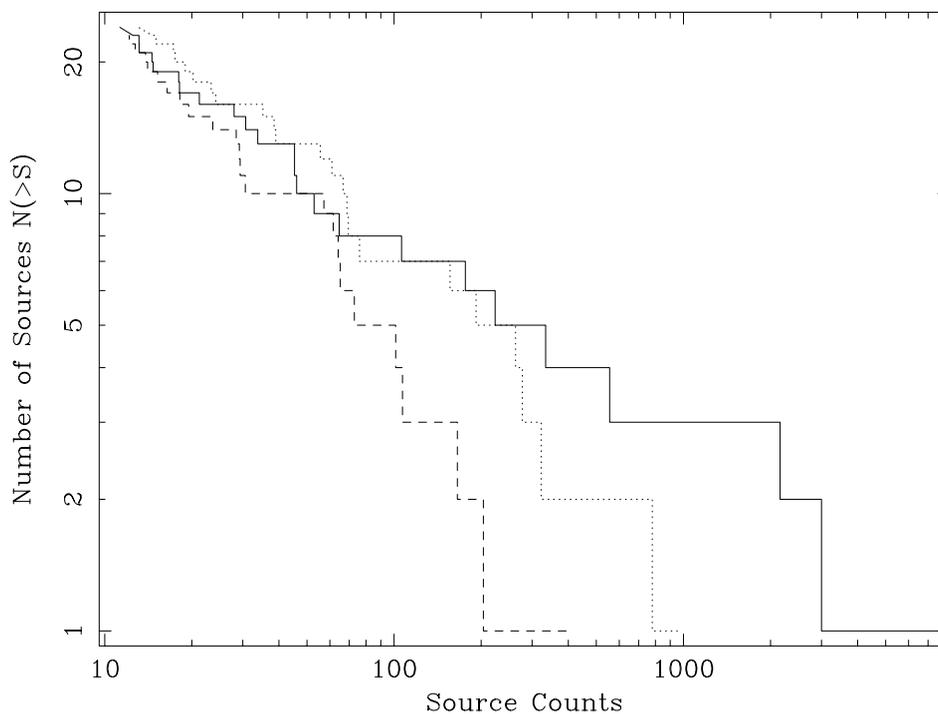


FIG. 17.—Luminosity function for disk sources. Shown are the luminosity functions for sources within 0.3 kpc of spiral arms (*solid line*), sources between 0.3 and 0.75 kpc (*dotted line*), and sources more than 0.75 kpc away from spiral arms (*dashed line*).

imately 10% of Galactic globular clusters contain X-ray sources. In the case of M81, two surveys of the globular cluster population report a total of 139 globular clusters including 98 within the *Chandra* field of view. Thus, 4% to 7% are coincident with X-ray sources. Di Stefano et al. (2002) find 25% of confirmed clusters in their M31 field of view contain X-ray sources and 10% of all globular cluster candidates have X-ray sources. They also report that most of the luminous M31 X-ray sources are in globular clusters. In contrast, only one of the 11 brightest M81 X-ray sources, *Einstein* source X7, is coincident with a globular cluster.

In general, there are remarkably few counterparts to the resolved X-ray sources identified in our assessment of the extensive literature and available archival images of M81. If the majority of the resolved sources are XRBs, then they have companion stars and accretion disks that may be detectable in optical light. The *HST* images of M81 approach a limiting magnitude of  $V \sim 27$  mag or  $M_V \sim -0.5$  mag. Thus, only O and B main-sequence or giant companions or highly luminous accretion disks from XRBs in active states will be detectable by *HST*. Later-type companion stars will not appear in the optical data.

Low-mass XRBs are common in galaxies because they are long-lived and slowly evolving. The last encounter of M81 and its companion galaxy M82 occurred some 500 Myr ago based on the study of the ages of young star clusters in M82 (de Grijs, O’Connell, & Gallagher 2001). If the onset of the last major star formation episode in the bulge of M81 was triggered by this encounter, then the most massive members of the current population of main-sequence stars have masses  $\lesssim 2.5 M_{\odot}$  (Maeder & Meynet 1988). If these constitute the population of companion stars in the currently active XRBs, then the resolved bulge sources are mostly low-mass XRBs. They will not have detectable optical counterparts because they do not have O, B, or giant star companions (and because of the bright, amorphous optical background of the bulge). In contrast, on-going star formation along the spiral arms should produce a population of high-mass XRBs with massive O and B star companions. This environment is, however, also the location of obscuring atomic and molecular gas. The few correlations with H II regions suggests some of the X-ray sources are located in star-forming regions that may be populated by massive stars. The high percentage of *HST* potential counterparts identified in the disk relative to the bulge also suggests an abundance of early-type stars in the vicinity of the disk sources and, potentially, a preference for high-mass XRB systems in this environment. This is consistent with the distribution of XRBs in our Galaxy, where high-mass XRBs are concentrated toward the Galactic plane and along spiral arms, while low-mass XRBs show a concentration toward the Galactic center (Grimm et al. 2001).

### 7.2. The Brightest M81 Sources

In-depth analysis of three of the four brightest sources in the M81 field was presented in § 4 and of the third brightest source in Swartz et al. (2002). Interestingly, all three of the brightest non-nuclear sources are far from typical XRBs as seen in our Galaxy. SN 1993J is a supernova, *Einstein* source X6 is a rare ultraluminous X-ray source with possible optical and radio counterparts, and source number 132 is an exceptionally bright and hot supersoft source candidate (Swartz et al. 2002).

#### 7.2.1. SN 1993J

SN 1993J appears to be evolving as expected based on the standard CSM interaction model of Chevalier (1982; Fransson et al. 1996), though a complete picture incorporating models of the exploding star and its pre-supernova environment awaits detailed numerical calculation. The X-ray properties of SN 1993J reported here provide an important constraint on any future theoretical investigations because the X-ray light curve is declining steadily, even at  $\sim 7$  yr, whereas the most-detailed numerical simulations to date (Suzuki & Nomoto 1995) predicted the light curve would drop precipitously long ago unless the CSM were clumpy. A clumpy CSM would produce a varying light curve with episodes of high X-ray flux occurring whenever clumps are overtaken by the outgoing shock wave (Chugai 1993). In this scenario, the CSM consists of a rarefied wind embedded with relatively dense clouds and the X-rays emanate from the shocked gas of the clouds with little or no reverse shock emission. This is not what is observed spectroscopically. The spectrum of SN 1993J is best modeled with a combination of thermal emission from a reverse shock and a hard component from a forward shock.

#### 7.2.2. Einstein Source X6

The multiwavelength properties of *Einstein* source X6 are intriguing. The X-ray spectrum of the source is best fitted with a disk blackbody model. In this model, the X-rays come from the inner portions of an accretion disk surrounding a compact object. The inferred mass of the central object is  $\sim 18 M_{\odot}$  assuming the innermost disk radius derived from the model corresponds to the last stable Keplerian orbit of a nonspinning black hole. The X-ray model-derived bolometric luminosity is near the Eddington limit for an object of this mass. The X-ray flux from X6 has been persistent throughout the  $>20$  yr of observation.

X6 is located within a  $5''$  diameter ( $\sim 90$  pc) SNR candidate according to Matonick & Fesen (1997) based on a high [S II]/H $\alpha$  ratio indicative of collisional excitation in the cooling region behind a SNR shock. There are no emission lines present in the X-ray spectrum of X6 and an optically thin thermal plasma model is a notably poorer fit to the X-ray data. The X-ray morphology of X6 is that of a point source with no evidence for extension. Thus, no X-ray evidence, besides a steady flux, supports the conjecture that X6 is a SNR.

A weak radio source is present at the location of X6. Synchrotron emission is observed at radio wavelengths from relativistic electrons accelerated in SNR shocks and in jets emanating from some (Galactic) XRBs. A radio (or optical) light curve of the source at the location of X6 has not yet been constructed. The radio source was present at 3.6 cm in late 1994 but not seen in a 6 cm image taken in late 1999. Analysis of other radio images is in progress. If the radio source proves to be variable, then it is not from a SNR. The observed radio flux density of  $\sim 95 \mu\text{Jy}$  is typical of, for example, Magellanic Cloud SNRs (Filipovic et al. 1998) after accounting for the disparate distances. In comparison, radio jets associated with Galactic XRBs are weaker except during extreme outbursts.

There is also an optical point source coincident with X6. If associated with X6, the optical emission may either be from a moderately massive, O9–B1, companion, which may

be a Be star, or from the accretion disk itself but does not come from an extended source at *HST* resolution.

X6 can be compared to well-studied nearby XRBs. An example of a high-mass system with a massive compact accretor is Cyg X-1 (e.g., van Paradijs 1995). The optical counterpart to Cyg X-1 is an O9.7 supergiant with colors similar to those of the X6 counterpart but with the higher optical luminosity of a supergiant compared to a main-sequence star. The putative black hole in Cyg X-1 exceeds  $7 M_{\odot}$  and is most probably  $\sim 16 M_{\odot}$ . Cyg X-1 is a persistent X-ray source as is X6. It displays the characteristic high soft and low hard states typical of black hole XRBs (Tanaka & Lewin 1995) and does not exceed an X-ray luminosity of  $\sim 2 \times 10^{38}$  ergs  $s^{-1}$ . Cyg X-1 is radio bright during its low hard state with a flux of  $\sim 15$  mJy or  $0.007 \mu\text{Jy}$  if it were placed at the distance of M81. Scaling this value upward by the ratio of the X-ray luminosities of X6 to Cyg X-1 in its low hard state ( $\sim 700$ ) results in a radio flux density of only  $6 \mu\text{Jy}$ , which would not be detectable.

An example of a low-mass system with a massive compact object and strong radio emission is the microquasar GRS 1915+105 (e.g., Mirabel & Rodriguez 1999). This system is a rapidly variable X-ray and radio transient reaching a peak X-ray luminosity of  $\sim 1.5 \times 10^{39}$  ergs  $s^{-1}$  in its high-soft state, comparable to X6, and an average luminosity of  $\sim 3.7 \times 10^{38}$  ergs  $s^{-1}$ . High extinction along the line of sight to GRS 1915+105 obscures the optical counterpart and accretion disk. Near-infrared spectroscopy (Greiner et al. 2001), however, shows the companion to be a K–M main-sequence star and, along with the orbital period, constrained the compact object mass to be  $14 \pm 4 M_{\odot}$ . GRS 1915+105 is a strong radio emitter. Scaling to the distance of M81 and to the X-ray luminosity of X6 (a factor of  $\sim 13$  when GRS 1915+105 is in its hard state) results in a radio flux density of about one-half the X6 value.

Thus, while monitoring at many wavelengths is required before any definitive statement can be made, it is intriguing to consider X6 may be an X-ray–bright and radio–bright member of the class of microquasars (see Mirabel & Rodriguez 1999 for a review) consisting of an accreting black hole with a radio–bright jet but with unusually steady X-ray flux.

### 7.2.3. The M81 Nucleus

The X-ray properties of the nucleus of M81 are difficult to deduce from the present data set because of severe pile-up. A relatively weak spectrum extracted from the readout trail was analyzed and found to be a power law of photon index  $\Gamma = 1.98 \pm 0.08$ , consistent with numerous previous X-ray studies. The presence of Fe K $\alpha$  emission could not be confirmed because of the lack of counts above  $\sim 5$  keV. Variability of the source also could not be assessed. However, it was shown, with the aid of the high angular resolution of the *Chandra* image, that the contribution to the nuclear spectrum from thermal emission is small or nonexistent. Any thermal X-ray component present in the region is consistent with an extrapolation of the unresolved bulge emission observed surrounding the nucleus and extending over an  $\sim 4$  kpc diameter region.

### 7.3. The M81 Bulge

In addition to 53 X-ray sources resolved in the *Chandra* image, the bulge of M81 emits  $\sim 10^{39}$  ergs  $s^{-1}$  in unresolved emission. This is  $\sim 12\%$  of the total non-nuclear emission

from the entire galaxy and is distributed over an  $\sim 2'$  radius region centered on the nucleus. Both the resolved sources and unresolved emission trace the optical light from the old population of bulge stars.

If the unresolved emission is also produced by stellar systems, then they are systems distinct from the resolved sources because extrapolation of the luminosity function of the resolved sources contributes  $< 10\%$  of the unresolved emission. The possible X-ray–luminous stellar systems below the detection limit are massive OB stars, Be XRBs, CVs, RS CVn stars, and, at a lower luminosity, late-type stars. However, individual late-type stars have X-ray luminosities only of order a few  $10^{27}$  to a few  $10^{28}$  ergs  $s^{-1}$ , requiring some  $10^{12}$  stars to produce the unresolved emission.

Massive OB stars with colliding winds can be strong X-ray emitters but are rare. None are found in the bulge of M81 (Devereux et al. 1997). Be XRBs are young high-mass systems and the Be companion star is optically bright. They are therefore also unlikely to be abundant in the galactic bulge.

CVs are short-period (typically  $< 1$  day) binaries consisting of a white dwarf and a late-type low-mass companion (Warner 1995). They are numerous and are long-lived. The magnetic CVs, with a magnetic white dwarf, are known to have X-ray luminosities as high as  $\sim 10^{32}$  ergs  $s^{-1}$ . The space density of magnetic CVs in the solar neighborhood is  $\sim 10^{-6}$  pc $^{-3}$  (Warner 1995), while the stellar density is about  $0.7 M_{\odot}$  pc $^{-3}$  (Allen 1973). This implies the density of magnetic CVs is  $\sim 10^{-5} M_{\odot}^{-1}$ . If M81 has a similar space density of magnetic CVs, then there will be roughly  $10^5$  CV systems in the bulge of M81. If about 10% are active (a rough estimate based on the properties of the local systems), then only  $\sim 10^{36}$  ergs  $s^{-1}$  of the unresolved bulge X-ray emission can come from CVs.

RS CVn systems, composed of chromospherically active G or K stars with late-type main-sequence or subgiant companions, also have high X-ray luminosities. Typical X-ray luminosities of RS CVn systems range from  $\sim 10^{29}$  ergs  $s^{-1}$  to  $\sim 3 \times 10^{31}$  ergs  $s^{-1}$  (Rosner, Golub, & Vaiana 1985). Thus, some  $10^7$  to  $10^{10}$  RS CVn systems are required to produce the unresolved bulge emission. If all stars in the bulge are  $\sim 1 M_{\odot}$  and half are in binary systems, then there are  $\sim 10^{10}$  binary systems in the bulge. Assuming about 20% of these systems become RS CVns and that G–K stars spend only a few percent of their lifetimes in their giant stage, an uncomfortably large fraction must currently be in an RS CVn phase.

Individually, therefore, none of these stellar systems can readily account for the observed unresolved X-ray emission from the M81 bulge. If, instead, some portion of the unresolved bulge X-ray emission is from hot diffuse gas, as suggested by its spectral distinction from the simple power-law shape of the resolved sources, then only a small fraction ( $\sim 0.02\%$ ) of the total bulge mass is needed to account for the observed emission. The X-ray emission, however, does not appear filamentary like the H $\alpha$  emission does (Devereux et al. 1995). A filamentary morphology would be expected if the emission is from ionization by shocks. A source for producing shocks is also not obvious. Devereux et al. (1997) suggest shocks originating from nuclear activity can account for the wispy “nuclear spiral” of H $\alpha$  emission confined to the central  $\sim 1'$ , but the unresolved X-ray emission is rather smoothly extended over a region of  $2'$  radius. While ionizing radiation from hot evolved post-AGB stars may produce the

observed UV excess in the core of M81 (O’Connell et al. 1992; Devereux et al. 1995), these stars do not produce adequate ionizing radiation in the *Chandra* energy band to account for the X-ray emission (Binette et al. 1994).

#### 7.4. The M81 Disk and Spiral Arms

One of the most spectacular features of M81 is its grand design spiral arm structure. The spiral arms trace the location of recent star-forming activity induced by the passage of spiral density waves. Applications of classical density wave models to M81 (e.g., Visser 1980) predict that material travels faster than the spiral pattern, entering an arm on the inside “upstream” edge. Stars forming at the spiral shock front travel at the local circular velocity of galactic rotation so that the youngest stars would be immediately downstream of the shock or toward the outside edge of the arm. The most massive stars are the quickest to evolve. They end their lives in core-collapse SN explosions leaving behind a neutron star or, perhaps, a black hole remnant. Supernova explosions produce X-ray emitting SNRs and compact stars in binaries may become XRBs. Thus, the spiral arms are not only the site of star formation but also a stellar graveyard and the birthplace of X-ray sources.

The brightest X-ray sources in the disk of M81 correlate spatially with the spiral arms. Accepting that the majority of the resolved sources are XRBs and that the X-ray flux is generally proportional to the mass accretion rate, then the brightest XRBs are young high-mass XRBs with high mass-transfer rates. The onset of mass-transfer in these systems, and hence of the X-ray-bright phase, can begin immediately following the formation of the compact object because of the strong stellar wind from the massive companion. This is in contrast to the low-mass XRBs in which mass transfer begins only after the companion star evolves to a (sub)giant stage or when the binary orbit has decayed sufficiently so that Roche lobe overflow can begin. Thus, the young high-mass systems become X-ray emitters while still within the spiral arm region of their origin. For this reason the luminosity distribution of the young XRBs in the spiral arms are expected to differ from the distribution of the older XRBs elsewhere in the galaxy. In particular, it will not show the characteristic luminosity break induced by aging of the XRB population as predicted by Wu (2001) and Wu et al. (2003a, 2003b).

Core-collapse supernova only come from stars more massive than  $\sim 8\text{--}10 M_{\odot}$  and are X-ray bright SNRs only for a relatively short time. They, too, should be found preferentially near their place of origin, the spiral arms.

## 8. CONTRIBUTIONS TO THE M81 X-RAY LUMINOSITY FUNCTION

The observed M81 X-ray luminosity functions reported by Tennant et al. (2001) prompted Wu (2001) and Wu et al. (2003a, 2003b) to consider the physical underpinnings that give rise to a cutoff in the luminosity function for the bulge sources and to the absence of this feature in the disk population. Wu (2001) showed that the shape of the luminosity function is governed to first order simply by the birth rates and (X-ray active) lifespans of the XRBs that dominate the luminosity function and hence is a measure of the star formation history of the local environment and of galaxy evolution in the broader context. Further investigation (Wu et

al. 2003a, 2003b) reveals that several complicating issues must be considered before this hypothesis can be rigorously applied. Some of these issues have been addressed in the present work.

The first issue is the presence of a population of SNRs. The onset and duration of the X-ray active phase of XRBs depends mainly on the donor star mass and its consequent evolutionary path, while the X-ray luminosity depends on the accretion rate. This is fundamentally different than the X-ray evolution of SNRs. Here we have shown, however, that SNRs are not important contributors to the total X-ray source population in M81 with the exception of SN 1993J, the fourth brightest source in the M81 field at the time of observation.

Another issue is the occurrence of XRBs in globular clusters. If capture processes govern the formation of XRBs in globular clusters, as seems likely to account for the excess of XRBs in these environments, then the characteristic lifetime of the XRB is not just correlated with the nuclear or orbital evolution timescales of the system but is also a function of the encounter frequency. However, only a few percent of the X-ray sources in M81 appear to be in globular clusters. As with Galactic globular cluster XRBs (Verbunt & van den Heuvel 1995), the impact on the luminosity function is further minimized by the fact that the globular cluster XRBs in M81 are not among the brightest X-ray sources. Again, the exception is *Einstein* source X7, the fifth brightest source in the field.

A third factor with potential impact to the basic hypothesis of Wu (2001) is the presence of XRBs with a nuclear-burning white dwarf accretor, i.e., members of the class of supersoft sources (e.g., Kahabka & van den Heuvel 1997). While the lifespans of these objects depend on the companion mass and mass-transfer rates as with other XRBs, only a narrow range of mass-transfer rates result in *steady* nuclear burning. Wu et al. (2003a, 2003b) argue, therefore, a narrow X-ray luminosity range for this source population and a sharp decline in the number of sources with luminosities above the Eddington limit for a Chandrasekar-mass accretor. Swartz et al. (2002) found nine supersoft source candidates in the M81 field. Six of these are relatively weak sources with luminosities in a narrow range around  $\sim 10^{37}$  ergs  $s^{-1}$ . The three brightest candidates, however, radiate at or above the Eddington limit depending on the adopted spectral model with one source (the third brightest in the entire field) approaching  $\sim 10^{39}$  ergs  $s^{-1}$ . Thus, the most important contribution to the luminosity function from supersoft sources is at the high-luminosity end and is dominated by one bright source. The effect of the weaker supersoft sources is obscured by the large number of other sources contributing at low luminosities.

The luminosity function for all non-nuclear sources detected within the  $D_{25}$  isophote of M81 is shown in Figure 18. Also shown are the luminosity functions of the supersoft sources, of X-ray sources spatially coincident with globular clusters, and with SNRs. As shown in Figure 18, these three populations all have relatively flat power-law luminosity functions and they affect only the bright end of the overall luminosity distribution. XRBs, the dominant population of X-ray sources in M81, however, have a steep luminosity function and hence determine the overall shape of the luminosity functions, especially at the faint ends. The break at the luminosity of  $\sim 4 \times 10^{37}$  ergs  $s^{-1}$  that we have found (see also Tennant et al. 2001) is therefore a character-

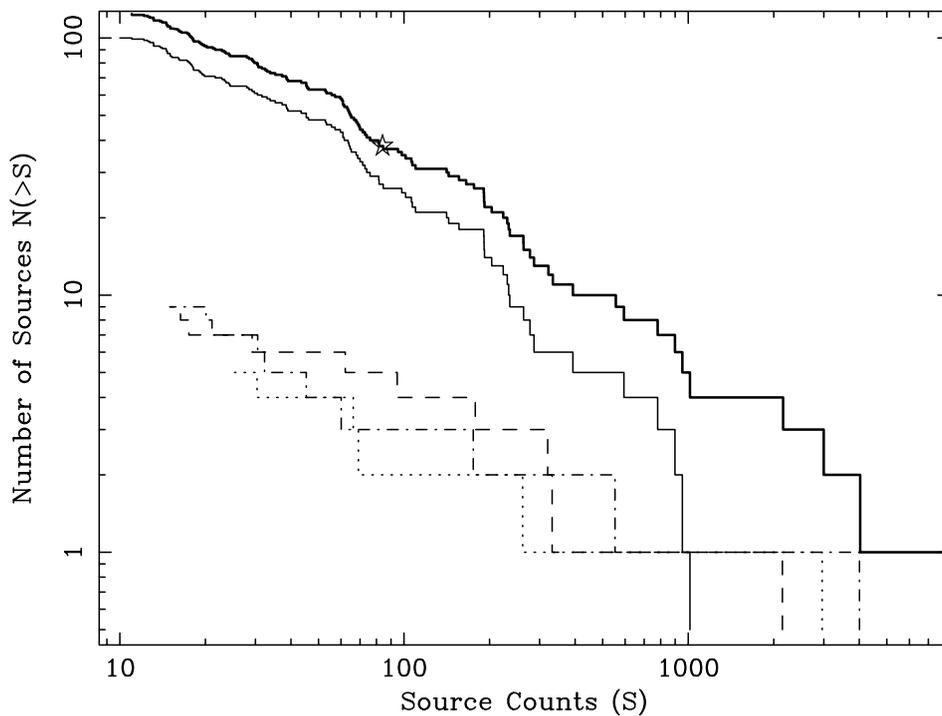


FIG. 18.—Observed X-ray luminosity function including all 123 non-nuclear X-ray sources detected within the  $D_{25}$  isophote of M81 (heavy solid line). Also shown are the luminosity functions of the SNRs (dotted line), of X-rays sources spatially coincident with globular clusters (dashed line), and of the supersoft sources (dot-dashed line). The luminosity function with these three populations and the ultraluminous X-ray source X6 omitted is shown as a thin solid line. The symbol ( $\star$ ) marks the division between bright sources for which spectral analysis has been reported in this work and of weak sources for which no spectral fits were made.

istic imprint of the XRBs. We have argued that the formation of such a break is due to the age of a population of XRBs which were born at a starburst episode in the recent past (Wu 2001; Wu et al. 2003a, 2003b). This break is distinguishable from another possible break, expected to occur at  $\sim 2 \times 10^{38}$  ergs  $s^{-1}$ , the Eddington luminosity of a  $1.5 M_{\odot}$  accreting object. The latter is attributed (Sarazin, Irwin, & Bregman 2001) to the presence of a population of neutron stars which accrete at rates close to the Eddington limit. Whether or not this break is visible in a given population depends on the relative proportion of neutron-star XRBs and black-hole XRBs. It also requires that the host galaxies (e.g., giant ellipticals) have a sufficiently large X-ray source population that the break becomes statistically significant. Nevertheless, we do see hints of this break in the luminosity function of the X-ray sources in M81 when we remove the SNRs, globular clusters XRBs, and the supersoft sources.

In summary, most of the factors complicating the simple birth-death model are unimportant for M81. Nevertheless,

careful examination of the brightest sources is warranted because they have the largest influence on the luminosity function and yet are certainly not typical of the dominant class of X-ray sources, the XRBs.

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