CALIBRATING THE BROAD BAND X-RAY TELESCOPE

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ABSTRACT

This paper describes the calibration of the two solid-state Si(Li) X-ray detectors and the X-ray telescopes that flew as part of Goddard Space Flight Center's Broad Band X-Ray Telescope (BBXRT) experiment on board the space shuttle Columbia in 1990 December. During the 9 day shuttle mission, BBXRT performed ~ 150 observations of 82 celestial sources. The content of the archive is summarized here. Although BBXRT had a relatively short life, it stands as a milestone in X-ray astronomy as being the first instrument to offer moderate spectral resolution over a wide bandpass (0.3–12.0 keV). Among other things, this paper discusses the effective area calibration of the instrument, the flux calibration and flux corrections for off-axis observations, the detector background, and optimal background subtraction techniques. The on-axis effective area calibration for the central detector elements was performed using data from the Crab Nebula, while other carefully selected targets were used for calibration of the outer detector elements. The remaining systematic uncertainties in the effective area calibration for point sources observed both on and off axis are generally less than 5%–10%. The energy scale is known to better than 0.5% at 6.0 keV for both detectors. The results presented here have an impact on the calibration of other medium resolution X-ray experiments such as the CCDs on board *ASCA* (*Astro-D*) as well as the *Advanced X-Ray Astrophysics Facility* detectors.

Subject headings: instrumentation: detectors — space vehicles — X-rays: general

1. INTRODUCTION

The Broad Band X-Ray Telescope was flown in 1990 December on board the space shuttle Columbia (STS-35) as part of Astro-1, the first NASA shuttle mission devoted entirely to astronomical observations. BBXRT consisted of two identical telescopes with lightweight, nested, thin-foil conical imaging mirrors (Serlemitsos 1988), which focused X-rays onto two segmented, cryogenically cooled, spectrophotometric Si(Li) diodes located at the focal plane. The mirrors were invented, designed, and built at the Goddard Space Flight Center (GSFC) Laboratory for High Energy Astrophysics; the detectors were supplied by Lawrence Berkeley Laboratory. The only solid-state detector and mirror combination flown in orbit prior to BBXRT was the Solid-State Spectrometer (SSS) on the *Einstein Observatory*. BBXRT is modeled after the SSS; however, BBXRT has much better energy resolution (10% compared to 20% at 0.8 keV), about 4 times the effective area at 1 keV, a factor of 3 larger bandpass, and a factor of 100 less internal background. Prior to the flight of BBXRT, the technique of X-ray spectroscopy was limited by either the poor energy resolution of proportional counter experiments or the

small bandpass and low efficiency of instruments with higher spectral resolution.

The large bandpass (0.3–12.0 keV) and good energy resolution of BBXRT ($\sim 2.5\%$ at 6 keV) combined with the extremely low detector background (1.5×10^{-3} counts s⁻¹ keV⁻¹ in each central detector element) make the instrument ideal for studying complex spectra and searching for X-ray emission and absorption features. The objectives of the BBXRT mission were to perform X-ray spectroscopy in the 0.3–12.0 keV band, to observe X-ray spectral features with particular emphasis placed on iron K lines, and to study broadband spectral variability. During its flight, BBXRT spent roughly 185,000 s pointing at celestial sources with typical integration times of 500–2000 s per observation. The BBXRT observation log, containing a complete list of all scientifically useful pointings, is given in Table 1. The targets observed include stars, X-ray binaries, supernova remnants, normal galaxies, active galaxies, and clusters of galaxies. Observations of the diffuse X-ray background, Earth's atmosphere, and the reflected solar spectrum are not listed in Table 1, but account for a large fraction of the total observing time.

This paper presents a detailed description of the calibration of the BBXRT experiment. The characteristics of the detector and mirrors are presented in § 2.1 and § 2.2, followed by a short description of the mission and the in-flight performance of BBXRT (§ 2.3). The detector gain, resolution, and incomplete charge collection are summarized in §§ 3.1–3.3. The Crab Neb-

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TABLE 1
BBXRT OBSERVATION LOG

Source	R.A. ^a	Decl. ^a	R.A. offset ^b	Decl. offset ^b	Roll ^c	Start ^d	Exp ^e	D/N ^f	GR ^g	Angle ^h	Rate ⁱ	Class ^j
GAM-CAS	13.413	60.445	−0.055	−0.086	19.3	1.2061	233.3	N	1284.4	5.4	7.82	MXRB
CAPELLA	78.248	45.950			40.0	2.2195	1947.2	MN	1218.2	−1.0	2.75	RSCVn
CAPELLA	78.248	45.950			39.0	2.2836	1706.1	B	1136.0	−1.0	3.15	RSCVn
CRAB	82.870	21.978			154.0	2.4907	112.3	D	948.0	−1.0	1127.36	SNR
CRAB	82.870	21.978	0.144	0.278	153.2	2.4935	440.6	D	943.0	−1.0	1418.07	SNR
CYG X-3	307.657	40.787			241.0	2.7306	384.9	N	1136.1	2.7	240.63	LMXB
PERSEUS	49.123	41.331	0.023	−0.032	120.7	2.7828	478.1	N	1418.4	2.2	9.46	Cluster
LMC X-2	80.325	−72.007			277.0	2.8329	31.1	D	1272.5	−1.0	16.01	LMXB
LMC X-2	80.325	−72.007			280.0	2.9765	43.2	N	1010.2	−1.0	12.04	LMXB
A754	136.660	−9.460	0.020	−0.020	330.6	2.9991	1454.8	D	1432.5	1.6	6.64	Cluster
CRAB	82.870	21.978	0.050	−0.001	354.1	3.0403	1270.1	N	1599.9	3.0	1519.20	SNR
CRAB	82.870	21.978			355.0	3.0550	1234.2	B	1367.9	1.0	1521.19	SNR
AR-LAC	331.664	45.496	−0.024	−0.045	22.7	3.0834	1456.4	D	1327.6	2.9	4.80	RSCVn
M81	147.865	69.304			37.0	3.1053	2734.5	MN	1476.3	−1.0	2.69	Starburst
CAS-A	350.292	58.540			183.0	3.1493	996.2	D	1186.4	−1.0	48.31	SNR
EZ-CMA	103.034	−23.864	0.062	0.129	256.7	3.1684	2522.0	MD	1216.3	8.5	0.90	W-Rayet
TON490	152.775	25.100	0.048	−0.023	342.2	3.2510	1061.9	D	1152.6	2.9	1.07	RL QSO
CTB109	345.000	58.633	0.292	0.122	186.8	3.2784	2237.4	D	1038.8	11.7	6.24	SNR
PUPAC	125.625	−42.800	−0.118	−0.031	317.7	3.3278	794.9	D	7317.6	5.5	33.83	SNR
0614+09	93.595	9.156	0.081	−0.082	40.7	3.3598	915.2	N	1023.7	6.8	54.03	LMXB
0614+09	93.595	9.156	0.011	−0.007	39.1	3.3728	406.1	N	1038.4	0.7	66.44	LMXB
0748−676	117.102	−67.623	0.084	0.067	280.6	3.3831	1363.6	D	1087.3	4.5	22.26	LMXB
A496	67.835	−13.363	−0.034	0.047	29.2	3.4126	2048.4	N	988.2	3.5	6.37	Cluster
1634+706	248.717	70.627			275.0	3.5768	2147.1	D	1122.4	−1.0	10.70	RQ QSO
A2319	289.908	43.841			194.0	3.6500	388.8	D	1363.0	−1.0	83.50	Cluster
CAPELLA	78.248	45.950			215.0	3.7433	118.4	N	1397.8	−1.0	10.49	RSCVn
PERSEUS	49.123	41.331			233.0	3.7570	199.7	N	952.5	−1.0	47.41	Cluster
LMC X-1	85.023	−69.768			280.0	3.7828	616.4	D	1151.8	−1.0	32.72	MXRB
NGC2110	87.443	−7.467	−0.030	0.033	301.6	3.7994	2455.3	N	1358.8	2.7	1.79	Seyfert 2
NGC4151	182.004	39.684			330.0	3.8331	893.6	D	1853.5	5.5	7.04	Seyfert 1.5
CAS-A	350.292	58.540			205.0	3.8515	106.9	D	1012.9	−1.0	137.77	SNR
MKN335	0.9380	19.925			205.0	3.8544	2081.1	MN	1470.4	2.0	2.83	Seyfert 1
MKN335	0.9380	19.925			205.0	3.8800	232.2	N	1102.7	−1.0	2.33	Seyfert 1
MKN876	243.401	65.844			273.0	3.9106	322.0	D	955.7	1.6	5.53	Seyfert 1
Q1821	275.433	64.325			249.0	3.9425	388.8	N	1164.4	−1.0	2.67	RQ QSO
CYG X-2	325.654	38.091			301.0	3.9717	146.3	D	1433.3	0.9	326.45	LMXB
CYG X-2	325.654	38.091			301.0	3.9735	864.0	D	2110.6	0.9	964.06	LMXB
CYG X-1	299.120	35.065	−0.015	−0.005	319.0	3.9837	1255.4	B	1073.3	0.8	212.04	MXRB
NGC3227	155.195	20.119			354.0	4.0044	1838.2	N	1447.3	−1.0	1.03	Seyfert 1
SCO430	67.675	−61.546			362.0	4.0501	1261.5	MN	1049.0	−1.0	1.12	Cluster
CRAB	82.870	21.978			0.0	4.5160	1053.3	D	898.6	−1.0	322.38	SNR
CYG X-2	325.654	38.091	0.070	−0.015	208.4	4.5437	659.2	D	1041.0	3.4	699.02	LMXB
CYG X-2	325.654	38.091			209.0	4.5516	814.6	D	1116.4	2.5	325.55	LMXB
NGC4051	180.152	44.810			72.0	4.5681	2290.7	MN	1027.3	2.2	1.42	Seyfert 1
LMC X-1	85.023	−69.768			327.0	4.6117	1235.6	D	992.9	−1.0	45.56	MXRB
NGC1566	64.722	−55.056			308.0	4.6262	1252.8	N	1083.5	−1.0	1.09	Seyfert 1
SN1987A	83.958	−69.300			327.0	4.6530	244.7	D	880.5	−1.0	1.94	SNR
SN1987A	83.958	−69.300			327.0	4.6670	1365.1	D	1111.5	−1.0	4.28	SNR

TABLE 1—*Continued*

Source	R.A. ^a	Decl. ^a	R.A. offset ^b	Decl. offset ^b	Roll ^c	Start ^d	Exp ^e	D/N ^f	GR ^g	Angle ^h	Rate ⁱ	Class ^j
Q1821	275.433	64.326	2.616	0.426	181.9	4.6998	2170.8	B	1080.0	−1.0	16.01	RQ QSO
NGC1399	54.142	−35.612	−0.001	−0.009	124.5	5.0236	737.0	B	1424.6	0.5	3.33	Ellip. Galaxy
NGC1399	54.142	−35.612	−0.004	0.004	122.6	5.0495	4202.5	B	1234.9	0.3	12.36	Ellip. Galaxy
BY-DRA	278.190	51.680	−0.057	0.090	180.2	5.1181	1126.0	D	1109.4	5.6	3.12	K Star
A2256	256.685	78.713	−0.513	0.005	198.4	5.1323	2566.1	MN	1100.6	6.0	3.83	Cluster
Q1821	275.433	64.326	−0.155	0.080	178.4	5.1620	4822.1	D	2759.1	6.3	8.57	RQ QSO
0614+09	93.595	9.156			60.0	5.2252	328.3	D	1070.1	−1.0	8.32	LMXB
IC443	93.583	22.817	0.200	−0.077	62.5	5.3403	471.4	N	1033.1	12.0	3.73	SNR
IC443	93.583	22.817	0.164	0.038	62.7	5.3458	1198.9	B	1019.4	9.3	15.03	SNR
A2256	256.685	78.713			280.0	5.3801	207.4	D	998.0	−1.0	5.18	Cluster
PERSEUS	49.123	41.331			165.0	5.3870	2166.3	MN	952.8	−1.0	4.93	Cluster
LMC X-1	85.023	−69.768			40.0	5.4642	465.2	N	885.9	−1.0	46.42	MXRB
SN1987A	83.958	−69.300	−0.157	−0.023	38.9	5.4697	2163.9	B	989.4	3.6	2.12	SNR
LMC X-1	85.023	−69.768			40.0	5.4950	267.8	D	1043.1	−1.0	44.55	MXRB
A262	27.475	35.917	0.235	0.107	193.8	5.5080	2581.3	B	996.1	13.1	1.57	Cluster
EV-LAC	341.162	44.075	0.096	0.068	223.0	5.5681	2210.5	B	1043.2	5.8	1.58	M4 Star
NGC4151	182.004	39.684			81.0	5.6160	691.2	D	1488.3	6.0	6.31	Seyfert 1.5
COMA-CL	194.292	28.224			71.0	5.6251	250.5	D	1114.4	−1.0	8.64	Cluster
0851+202	132.989	20.300	0.198	−0.032	291.0	5.6593	1878.7	B	1214.5	11.3	1.17	BL Lac
NGC2992	145.821	−13.903			316.0	5.6829	86.1	D	1671.4	−1.0	1.61	Seyfert 2
A496	67.835	−12.637	−0.017	0.724	250.7	5.7254	760.1	N	989.4	−1.0	5.85	Cluster
0114+65	18.674	65.026	0.018	0.018	306.8	5.7610	517.2	D	1031.3	1.2	6.80	MXRB
H0538+61	84.566	60.834	−0.005	−0.005	248.1	5.7677	2458.7	MN	1334.6	0.3	3.74	CV (AM Her)
0548−32	87.208	−32.282			240.0	5.8008	184.5	D	1436.0	−1.0	7.11	BL Lac
N132D	81.376	−69.684			237.0	5.8042	214.7	D	1930.6	−1.0	10.67	SNR
SN1987A	83.958	−69.300	0.127	−0.010	239.6	5.8070	1036.8	D	1757.4	2.8	3.16	SNR
N132D	81.376	−69.684			238.0	5.8190	276.5	D	895.4	−1.0	15.95	SNR
MKN3	92.452	71.053	−0.059	−0.010	239.2	5.8330	2310.8	N	1462.8	1.3	1.10	Seyfert 2
NGC253	11.274	−25.561	−0.004	−0.026	280.0	5.8788	1671.2	D	1073.2	1.6	2.09	Starburst
NGC4151	182.004	39.684			160.0	5.9064	570.2	N	1779.9	4.0	8.00	Seyfert 1.5
NGC4151	182.004	39.684			159.0	5.9202	581.2	MD	1105.1	4.0	6.73	Seyfert 1.5
NGC4151	182.004	39.684			158.0	5.9270	1181.0	D	1871.7	0.0	8.19	Seyfert 1.5
RS-CVN	197.074	36.200	0.038	0.067	148.7	5.9410	741.0	D	1445.3	4.4	20.60	RSCVn
ZET-PUP	120.457	−39.861	0.108	0.018	219.0	5.9695	665.3	N	1981.9	5.1	2.63	OB Sgiant
VELA-X	128.413	−45.003	0.039	−0.036	226.3	5.9772	1148.9	B	1190.1	2.7	8.61	SNR
GAM-CAS	13.413	60.445			45.0	6.0364	60.5	N	1781.0	−1.0	2.99	MXRB
IC443	93.583	22.817	0.032	−0.001	34.8	6.1632	1439.7	MN	1159.2	1.8	12.03	SNR
ZET-ORI	84.559	−1.968	0.071	0.004	128.8	6.2255	1028.2	N	1099.2	4.3	1.57	O Star
ZET-ORI	84.559	−1.968	−0.029	0.004	129.4	6.2374	846.7	B	1033.0	1.7	2.83	O Star
CYG X-1	299.120	35.065			270.0	6.2548	805.3	D	5559.5	−1.0	144.21	MXRB
CAS-A	350.292	58.540			195.0	6.2665	123.6	D	1054.6	−1.0	144.46	SNR
PERSEUS	49.123	41.331	0.023	−0.032	120.7	6.2732	2524.5	N	973.9	2.2	43.62	Cluster
A262	27.475	35.917	0.031	−0.045	135.3	6.3378	1080.1	MN	976.8	3.1	3.40	Cluster
ALGOL	46.227	40.765	0.022	−0.029	123.2	6.3514	1523.9	N	950.1	2.0	7.29	RSCVn
0620−003	95.046	−0.320			41.0	6.3720	172.8	D	1054.0	−1.0	1.67	LMXB
VELA X-1	135.055	−40.357	−0.012	0.053	32.6	6.4132	3066.5	B	983.4	3.2	40.81	MXRB
0212+735	33.208	73.595	−0.314	−0.068	180.9	6.4594	311.0	D	954.0	6.7	2.73	RL QSO
MKN3	92.452	71.053	−0.259	0.038	125.0	6.4650	2511.1	MN	919.7	5.5	1.00	Seyfert 2

TABLE 1—*Continued*

Source	R.A. ^a	Decl. ^a	R.A. offset ^b	Decl. offset ^b	Roll ^c	Start ^d	Exp ^e	D/N ^f	GR ^g	Angle ^h	Rate ⁱ	Class ^j
2155–304	328.993	−30.465			253.0	6.5090	1123.2	D	1061.3	−1.0	16.88	BL Lac
MKN279	207.973	69.554	0.416	0.058	47.3	6.5321	475.2	N	929.0	9.4	1.25	Seyfert 1
NGC4051	180.152	44.810			67.0	6.5562	1399.7	D	1212.0	2.5	1.76	Seyfert 1
M15	321.888	11.947			288.0	6.5783	1078.2	D	1064.5	−1.0	17.17	LMXB
NGC4151	182.004	39.684			99.0	6.6052	742.5	N	886.9	4.5	4.34	Seyfert 1.5
NGC4151	182.004	39.684			98.0	6.6210	1382.4	D	1390.2	1.5	5.64	Seyfert 1.5
2155–304	328.993	−30.465	0.022	−0.050	343.1	6.6495	1503.4	B	1282.0	3.2	37.22	BL Lac
0836–42	128.912	−42.714	0.043	0.032	339.2	6.6858	1611.4	D	1508.8	2.7	20.75	LMXB
NGC1068	40.030	−0.225	0.021	0.000	300.3	6.7140	2975.4	MN	1264.4	1.3	2.30	Seyfert 2
0548–32	87.208	−32.282	0.088	0.022	277.7	6.7883	578.9	N	2052.6	4.7	6.07	BL Lac
0548–32	87.208	−32.282	−0.009	0.036	277.3	6.7950	804.8	N	1182.9	2.2	4.18	BL Lac
0548–32	87.208	−32.282	0.090	0.010	276.5	6.8044	656.4	N	1040.0	4.6	5.63	BL Lac
44IBOOA	225.535	47.848	0.081	0.001	134.9	6.8240	1672.1	D	1434.1	3.3	4.26	Contact binary
X-PER	58.063	30.900	0.028	−0.010	332.3	6.9917	858.3	N	1225.6	1.6	12.46	MXRB
1426+428	216.650	42.896			305.0	7.0084	447.5	D	1810.3	−1.0	7.05	BL Lac
1426+428	216.650	42.896			305.0	7.0136	371.0	D	1962.1	−1.0	6.93	BL Lac
1426+428	216.650	42.896			305.0	7.0183	1370.2	D	1220.4	−1.0	9.82	BL Lac
A665	126.575	66.011	0.011	0.010	299.3	7.0398	2715.7	B	1727.1	0.7	2.18	Cluster
NGC2110	87.443	−7.467	0.029	0.005	351.6	7.1021	2488.5	MN	1116.0	1.8	2.10	Seyfert
0212+735	33.208	73.595	0.098	−0.098	65.0	7.1632	673.9	D	843.6	6.1	0.94	RL QSO
0212+735	33.208	73.595	−0.034	−0.006	65.6	7.1778	1313.2	MN	1074.4	0.7	0.95	RL QSO
1634+706	248.715	70.627	0.015	−0.008	227.8	7.2127	3187.6	B	998.7	0.6	1.93	RQ QSO
NGC3227	155.195	20.119			350.0	7.2602	86.4	D	1044.9	−1.0	3.83	Seyfert 1
CEN X-3	169.758	−60.349			40.0	7.2646	1640.7	D	7209.9	−1.0	105.15	MXRB
Z-CAM	124.915	73.273			28.0	7.2910	110.1	D	819.4	−1.0	2.55	CV
M82	147.935	69.907	0.136	−0.023	26.9	7.2931	743.9	N	898.7	3.1	2.18	Galaxy
Z-CAM	124.915	73.273	0.191	−0.021	49.2	7.3025	791.4	N	914.1	3.5	0.74	CV
M82	147.935	69.907	0.143	−0.025	28.2	7.3123	1123.7	N	978.2	3.3	2.62	Galaxy
A262	27.475	35.917	0.203	0.022	149.1	7.3514	1898.0	B	936.0	10.0	1.99	Cluster
A262	27.475	35.917	0.023	−0.072	149.5	7.3753	855.4	MN	913.8	4.5	2.62	Cluster
BD61DEG	163.150	60.736			40.0	7.3876	121.8	D	1085.7	−1.0	1.62	flare star
M49	186.808	8.276	0.176	−0.003	12.8	7.3910	757.2	D	1155.4	10.4	1.43	Ellip. Galaxy
3C273	186.639	2.329	0.206	0.010	83.9	7.4380	988.1	MN	838.5	12.4	5.20	RL QSO
3C273	186.639	2.329			81.0	7.4500	1537.3	D	1080.2	−1.0	8.33	RL QSO
II-PEG	358.121	28.355	0.254	−0.005	175.5	7.4742	841.6	D	952.8	13.5	1.16	K2 Sgiant
II-PEG	358.121	28.355	0.008	0.016	174.4	7.4841	1675.5	N	997.7	0.5	5.49	K2 Sgiant
M82	147.935	69.907	0.170	−0.011	62.9	7.5086	138.2	N	878.5	3.6	2.36	Galaxy
1218+30	184.713	30.454	0.083	−0.008	41.1	7.5150	1346.8	D	1261.7	4.3	2.52	BL Lac
A262	27.475	35.917	0.080	0.039	169.9	7.5574	1136.3	N	908.5	4.5	3.04	Cluster
M15	321.888	11.947			289.0	7.6164	345.6	N	1178.4	−1.0	2.82	LMXB
M15	321.888	11.947			289.0	7.6204	211.7	N	1080.1	−1.0	20.83	LMXB
TYCHO	5.6380	63.860	−0.035	−0.030	290.1	7.6864	895.9	N	952.9	2.0	47.95	SNR
MKN335	0.9384	19.925	0.044	0.016	153.7	7.7498	786.2	N	1020.1	2.6	1.62	Seyfert 1
ZET-PUP	120.457	−39.861	−0.063	0.158	291.3	7.7670	1095.8	D	1855.7	9.9	1.97	OB Sgiant
0851+202	132.989	20.300	−0.005	−0.040	320.3	7.8160	1468.8	B	1129.2	2.4	0.99	BL Lac
0237–230	39.4700	−23.368	0.055	−0.088	155.8	7.8560	1408.3	B	1189.7	6.1	1.80	RL QSO
0237–230	39.4700	−23.368	−0.011	0.013	157.1	7.8745	1658.4	B	1323.7	1.0	1.19	RL QSO
CAR+WR25	160.671	−59.413	0.169	0.032	287.4	7.9000	1433.1	D	1687.5	5.5	8.68	W-Rayet

TABLE 1—*Continued*

Source	R.A. ^a	Decl. ^a	R.A. offset ^b	Decl. offset ^b	Roll ^c	Start ^d	Exp ^e	D/N ^f	GR ^g	Angle ^h	Rate ⁱ	Class ^j
YY-GEM	112.858	31.980	0.062	−0.012	262.1	7.9396	462.8	N	1845.6	3.2	2.02	M binary
SIG-GEM	115.047	29.006	0.043	−0.015	260.5	7.9451	1045.5	N	1168.5	2.4	4.62	K1 Sgiant
0212+735	33.208	73.595	0.040	0.117	348.0	7.9939	1856.9	N	1358.0	7.1	1.04	RL QSO
24-UMA	142.524	70.053	0.253	−0.065	243.2	8.0155	723.3	B	2022.9	6.5	3.11	G4 Sgiant
M82	147.935	69.907	0.197	−0.032	269.8	8.0536	2599.7	B	1173.8	4.5	2.40	Galaxy
1E1048.5	162.140	54.343			257.0	8.0890	521.0	D	6609.4	−1.0	3.74	CV (AM Her)
ZET-ORI	84.559	−1.968	−0.021	0.003	359.1	8.1424	699.5	MN	1395.4	1.2	2.13	O Star
1700+64	255.169	64.274	−0.099	0.014	218.2	8.1609	1901.1	D	1113.3	2.7	2.13	RL QSO
A2256	256.685	78.713	−0.134	0.003	217.9	8.1856	1701.3	N	999.2	1.6	4.70	Cluster
PUPAB	125.250	−42.683	0.443	0.357	69.1	8.3875	2719.3	B	1056.2	29.0	37.37	SNR
PUPAB	125.250	−42.683	0.333	0.101	69.1	8.4514	2937.6	B	1079.8	15.9	48.35	SNR
M87	187.073	12.667	0.018	0.207	359.9	8.5100	1712.6	MN	914.7	12.4	9.21	Radio Galaxy

^a Nominal right ascension and declination of source in decimal degrees (for epoch 1950.0).

^b Offset of the pointing direction of the A-system telescope from the nominal R.A. and Decl. in decimal degrees (epoch 1950.0), given as $R.A._{nom} - R.A._{aspect}$ and $Decl._{nom} - Decl._{aspect}$. Numbers are supplied only if there exists an aspect solution derived from data taken with the aspect camera. Specific details about aspect solutions can be obtained through the HEASARC at GSFC.

^c Roll angle of the A-system telescope (ϕ) in degrees. If no aspect solution exists, the roll angle is only an approximate value.

^d Start time is given in units of decimal days of MET measured from 1990 December 2, 06:49:01 UT.

^e Exposure time in seconds.

^f Indicator of shuttle day or night: N = night; D = day; MN = mostly night (>75%); MD = mostly day (>75%); B = both, mixed.

^g Mean detector guard rate as defined in § 5.1.

^h Average off-axis angle (θ) in arcminutes as derived from the nominal and aspect R.A.s and Decl.s (cols. [2]–[5]). When an angle but no R.A. or Decl. offset is given, that angle is derived from ray tracing. A value of −1 indicates that the angle has not yet been calculated. A ray-tracing program is available from the HEASARC that allows observers to determine their own off-axis angles and to confirm our aspect solutions.

ⁱ Total count rate in all 10 pixels.

^j Type of object.

ula data used for calibration are presented in § 3.4, followed by a discussion of the differences between the A and B detectors (§ 3.5). The effective area of the telescope as well as vignetting and flux corrections for off-axis observations are discussed in § 3.6, while the method used to determine the detector efficiencies is presented § 3.7. The current mirror-plus-detector effective area curves for both on- and off-axis observations are discussed in § 3.8. The description of the effective area calibration is followed by a discussion of the flux calibration (§ 4). Finally, a complete discussion of contributions to the detector background and background rejection techniques are presented in § 5, along with a prescription for background subtraction (§ 6). The remaining uncertainties in the calibration are summarized in § 7.

2. THE BBXRT INSTRUMENT AND PERFORMANCE

An artist's concept of the BBXRT detector and mirror assembly is shown in Figure 1. The instrument was 4.2 m in length, 1 m in diameter, and weighed approximately 680 kg. All of the optical devices (i.e., the telescopes, the aspect camera, and the star tracker) were mounted together on the optical plate. During the mission, snapshots of stars were obtained with the aspect camera (a charge injection device with a $4^\circ \times 6^\circ$ field of view) for real-time aspect determination, while the star tracker was used to update the pointing system reference. The X-ray focusing optical system provided a collecting area

of $\sim 750 \text{ cm}^2$ at 1.5 keV and $\sim 300 \text{ cm}^2$ at 7 keV for the entire focal plane (both detectors).

2.1. The BBXRT Detectors

The physics of solid-state detectors has been discussed extensively in the literature (e.g., Fraser 1989, and references therein). Each BBXRT detector, designated by “A” or “B,” consisted of a silicon block with a grooved surface, segmenting it into 5 spatial elements or “pixels” (Fig. 2, *lower panel*). The grooves were 0.5 mm wide and were covered with an opaque mask that also occulted 0.5 mm of the detector on either side of the groove. The mask covered a nonnegligible area of 1/36 on the sky, but was necessarily placed over the boundaries between the pixels to prevent those events falling near the boundaries from being detected in more than one pixel. Each of the pixels was equipped with its own external amplifier. The radius of the central pixels (designated A0 or B0) was 5 mm giving a field of view of 3/6, and the total diameter including the outer 4 pixels was 19 mm or 17/3. Since the central detector elements were smaller than the outer elements, they had about one-fourth of the background and hence provided greater sensitivity.

The detectors were formed by evaporating $\sim 200 \text{ \AA}$ of gold as a thin metal p-type contact onto the front, ungrooved, surface of a Si(Li) n-type semiconductor. A film made of 4000 $\text{\AA}$ of Parylene N (C_8H_8) and 2000 $\text{\AA}$ of aluminum, supported by an 86% transmitting nickel mesh, was placed in front of each

FIG. 1.—Artist's conception of the BBXRT detector and mirror assembly that was flown on the space shuttle Columbia

FIG. 2.—Schematic diagram showing the orientation of the BBXRT detectors with respect to the aspect camera. This figure also illustrates the orientation of the pixels on the celestial sphere. The roll angle, ϕ , is defined such that, when $\phi = 0$, the top of the camera and the top of pixel A4 point north. The offset between the A and B detectors (discussed in § 2.3) is not shown.

detector and served to filter out stray light or any UV component in the focused radiation. The various characteristics of the BBXRT detectors are summarized in Table 2. The detectors resided inside evacuated cryostats that were in thermal contact with cryogenic coolers containing solid argon (Fig. 1) via a 60 cm long connection. To reduce the number of thermally excited carriers in the silicon and to ensure good operation of the field effect transistor (FET) charge amplifier, the detectors were maintained at a temperature of 108–112 K during operation. A tantalum sheet surrounded the cryostat and was used as a shield against low-energy gamma rays. Outside this tantalum sheet was a plastic scintillator that acted as a charged particle guard and covered over 3π sr as viewed from the detector. Also, each detector was equipped with a calibration source holder containing Fe^{55} . During the mission, the calibration source could be moved into the field of view of the detector to monitor changes in the gain or energy resolution.

The central pixels had an on-orbit energy resolution of ~ 100 eV FWHM ($\Delta E/E \sim 10\%$) at 0.9 keV and ~ 155 eV FWHM at 6 keV ($\Delta E/E \sim 2.5\%$), while the outer pixels had a slightly poorer resolution of ~ 170 eV FWHM at 6 keV ($\Delta E/E \sim 3.0\%$). The signal processing electronics gave each pixel 512 energy channels. The widths of channels 1–255 are ~ 16 eV; the widths of channels 256–511 are ~ 32 eV; channel 512 is an overscale channel. The physically smaller central detector elements had a lower capacitance, hence a smaller leakage current. This resulted in a low-energy noise threshold of $\lesssim 0.3$ keV, a few tenths of a keV less than that of the outer elements. The lowest usable channels in A0 and B0 are channel 16 and channel 17, respectively, which corresponds to ~ 0.3 keV. This ranges from channels 25 to 30 in the outer pixels, which corresponds to ~ 0.5 keV (see Table 7 below and § 3.8.2). The discrete low-energy cutoffs are due to setting the discriminator

TABLE 2
TECHNICAL CHARACTERISTICS OF THE BBXRT DETECTORS

Characteristic	Value
Physical detector thickness	5 mm
Si(Li) active area	17 mm diameter
Si(Li) depletion depth	3 mm
Si(Li) bias voltage	550–600 V
Si(Li) operating temperature	108–112 K
UV/optical filter	C ₈ H ₈ and Al on an 86% transparent Ni mesh
On-axis effective area for one central pixel	~100 cm ² at 6 keV
Bandpass	0.3–12 keV
Energy resolution of central pixels (FWHM)	~155 eV at 6 keV ~100 eV at 0.9 keV
Energy resolution of outer pixels (FWHM)	~170 eV at 6 keV ~120 eV at 0.9 keV
Field of view of central pixels	3/6 diameter
Internal background of central pixels	1.5 × 10 ⁻³ counts s ⁻¹ keV ⁻¹
Time resolution	62.5 μs

thresholds just above the energy where the amplifier noise begins to dominate.

2.2. The X-Ray Mirrors and Point-Response Function

BBXRT used 10 cm long conical reflectors that approximated a Wolter type I mirror optical system. There were two adjacent, coaxial, and confocal arrays of cones (the primary and secondary) in each mirror assembly. The BBXRT mirrors were constructed from 0.013 cm thick aluminum foil that was bent into truncated cones and then dipped in acrylic resin. The function of the resin was to smooth the foil on small scales. The resultant rms microroughness was less than 3 Å. The reflecting surface was created by vacuum-depositing approximately 500 Å of gold on the resin (Serlemitsos 1988). Each mirror assembly consisted of 118 reflectors, and the focal length of the mirror system was 3.77 m. The mirror performance is summarized by Petre et al. (1992), and the mirror fabrication and mirror parameters are described in detail by Serlemitsos (1988) and Serlemitsos et al. (1991).

Although the nested foils gave a large throughput over a large bandpass, the telescope provided only a modest spatial resolution of 1/5 half-power radius (HPR). While this is partially due to the conical approximation to a Wolter I geometry, the 12" HPR intrinsic resolution of the design was far better than that obtained. The prime contributor to the degraded resolution was millimeter-scale ripples on the foil surface that resulted from the manufacturing process and were inadequately covered by the thin lacquer coating. A secondary source of blurring was the inaccurate mechanical fixturing of the foils.

We have determined the beam shape for the mirrors by comparing the preflight point-spread function (PSF) with flight data. This was done by calculating the fraction of source counts expected in each pixel assuming a certain beam shape. For bright sources that are closely aligned with the optical axis, the

in-flight data show more power in the outer elements than expected for a single Gaussian profile. At the focal plane, the integral power (beam profile) for each telescope is characterized by

$$P(<\Theta) = A \operatorname{erf}(\Theta/\sigma_1) + B \operatorname{erf}(\Theta/\sigma_2), \quad (1)$$

where erf stands for error function, $P(<\Theta)$ is the total power that is contained within an angular radius of Θ arcmin, $\sigma_1 = 1'.8$, and $\sigma_2 = 5'.8$. The first term in equation (1) represents the beam core, which contains 65% of the flux; the second term represents a halo, which contains 35% of the flux. For a source observed on axis: ~62% of the counts that reach the detector fall in the central pixel, ~21% fall on the mask between the pixels, and ~17% fall into the outer pixels. For a source that is observed near the edge of a pixel or on the mask, a larger fraction of photons is lost to the mask (up to 50%). It is necessary to correct for this loss when measuring absolute fluxes (see § 3.6). The energy dependence of the PSF is discussed in § 3.8.3.

2.3. Mission Description and Instrument Performance

BBXRT was launched on board the space shuttle Columbia (STS-35) on 1990 December 2, at 01:49:01 eastern standard time (UT 336/06:49:01), which defines a mission elapsed time (MET) of 0.0. The combined shuttle payload also contained the Hopkins Ultraviolet Telescope, Goddard's Ultraviolet Imaging Telescope, and the Wisconsin Ultraviolet Photo-polarimeter and is described in detail by Blair & Gull (1990). The BBXRT instrument was initially turned on about 3 hr after launch (MET = 0.13, given in decimal days), and the detector system remained active and performed flawlessly until about 6 hr before reentry. During the mission, the instrument alignment remained unchanged and the temperature of the A and B cryostats remained stable at values of 108 K and 112 K, respectively. None of the other instrument housekeeping parameters that were recorded during the mission (such as the detector voltages and the cryogen pressure and temperature) varied outside of their nominal values.

The telescope was mounted on the Two-Axis Pointing System (TAPS), which in turn was secured to the bay of the shuttle orbiter. To observe a target, the shuttle had to acquire and to maintain an attitude that allowed the source to stay within the TAPS gimbal range of $\pm 17^\circ$ for each axis (Serlemitsos et al. 1991). There were no stable pointings during the first 60 hr of the mission because of an improperly compensated gyro drift rate that allowed TAPS to drift off target. Once this drift was removed TAPS pointed stably, having a drift rate of less than $0'.1 \text{ s}^{-1}$. However, the absolute accuracy to which TAPS could acquire targets was only $2' - 5'$. This meant that for many observations real-time "tweaks" were needed to center a target. For observations performed during orbit night, attitude solutions were obtained using the aspect camera, with a typical accuracy of $\sim 1'$. For observations performed during orbit day, it is possible from TAPS and shuttle position data to determine to within $5'$ where BBXRT was pointing. However, by comparing the ratios of count rates in different detector elements to Monte Carlo simulations of the distribution of events in the

focal plane consistent with the mirror point-response function (§ 2.2), we are able to obtain fairly accurate off-axis positions for daytime observations. The uncertainty in each estimate is typically 0.5' for sources with medium to high count rates located within 5' of the center of the field of view, and $\sim 1' - 2'$ for weak sources or sources located more than 5' from the center. Although some off-axis angles have been calculated for sources lacking an aspect solution, this has not yet been done for $\sim 37\%$ of the observations listed in Table 1. The necessary ray-tracing software is currently available through the High Energy Astrophysics Science Archive Research Center (HEASARC) located at Goddard Space Flight Center.

Figure 2 illustrates the approximate orientation of the BBXRT detectors with respect to the aspect camera and projected onto the celestial sphere. The outer pixels of the A detector are labeled A1 to A4 counterclockwise on the sky. The telescope roll angle, ϕ (Table 1), increases counterclockwise and is defined such that, when $\phi = 0$, the top of the camera and the top of pixel A4 point north. The B detector is rotated by 180° with respect to the A detector such that A1 and B3 observe roughly the same area of the sky. Postflight analysis indicates a slight offset between the A and B telescopes (not shown in Fig. 2). The mean displacement of B from A is 0.822° at an azimuth of -63.24° . This azimuth is measured arbitrarily from the B3/B4 boundary and represents a 63° rotation through B4 toward B1. In other words, for a source centered in A0, the distribution of counts in the outer B pixels is maximized in B4. In general, this displacement leads to a lower count rate in B, since sources centered in A will be offset in B and a larger fraction of counts will fall on the B mask. A correction to account for the difference in observed count rates between A and B is not included in the effective area calculations. Therefore, all fluxes are currently measured with respect to the A system. Since the A system axis is taken as the nominal pointing position of the telescope, the term "on axis" refers to a source that is centered in the A detector.

3. CALIBRATION

3.1. Response Function

A Si(Li) detector response function has three basic components. First, the response function contains a Gaussian-shaped photopeak. Second, for incident photons having an energy of $h\nu > 1.84$ keV, a Gaussian-shaped escape peak (due to the escape of Si K X-rays) is observed 1.74 keV below the main photopeak. Finally, there are non-Gaussian components that occur in the response function below the full-energy peak of the main Gaussian. The physics of the non-Gaussian components is not well understood, but they represent charge loss mechanisms in the detector that result in an underestimation of the incident photon energy.

The shape of the response function for a monoenergetic photon can be described by

$$F(i) = G(i) + \text{Esc}(i) + \text{PC}_n(i), \quad n = 1, 2, 3, \quad (2)$$

where i is the detector channel number, $G(i)$ represents the main Gaussian photopeak, $\text{Esc}(i)$ represents the escape peak, and $\text{PC}_n(i)$ represents the partial charge collection. The partial

charge collection is a fairly complicated function (e.g., Fig. 2 in Krumrey, Tegeler, & Ulm 1988). There are as many as three major components to the partial charge: a step function at energies lower than the Gaussian photopeak (PC_1), a low-energy wing on the Gaussian photopeak (PC_2), and a tail that rises toward very low energies (PC_3). The specific shapes and magnitudes of these components vary from detector to detector (Shima et al. 1983), and they depend mainly on the thickness of the silicon dead layer. Further discussion of the partial charge collection in the BBXRT detectors is presented in § 3.3.

3.2. The Detector Gain and Resolution

The channel-to-energy relation was determined using Mn $K\alpha$ (5.895 keV) and Mn $K\beta$ (6.490 keV) from the in-flight Fe^{55} calibration source along with the lower energy atmospheric fluorescence lines of Ar (2.956 keV) and O (0.525 keV), as well as Si XIII (1.865 keV) and Mg XI (1.348 keV) from scattered solar X-rays. The gain is described by a quadratic function: $y = A + Bx + Cx^2$. Here, y is the channel in which the line peak is observed when fit with a Gaussian and x is the expected line energy. The gain was determined after channel doubling was properly accounted for. The best-fit gain coefficients for each pixel are listed in Table 3. The three columns labeled Start, Middle, and End give the lower energy boundary of the lowest channel (channel 1), the energy where the channel size doubles (channel 256), and the upper energy boundary of the highest channel (channel 512), respectively. The measured uncertainty in the gain at 5.9 keV is less than 1 channel (< 32 eV or $< 0.5\%$) for all pixels.

We have assumed atomic oxygen $K\alpha$ fluorescence to be at an energy of 0.525 keV, which is the value given by Bearden (1967). However, there are discrepancies in the literature as to the correct value for the oxygen K-edge energy, which may affect the assumed value of the fluorescence line. Bearden & Burr (1967) find the threshold energy (E_K) for photoejection of an electron from the K shell to be 0.532 keV, which places the edge at ~ 0.537 keV. However, Gould & Jung (1991) calculate E_K for atomic oxygen to be 0.546 keV. Scaling up the oxygen fluorescence line by the same amount places it at 0.540 keV. This would yield a remaining systematic offset of 15 eV (1 channel width) in the gain at low energies and would primarily impact the analysis of soft X-ray spectra with a high signal-to-

TABLE 3
GAIN PARAMETERS

Detector	A	B	C	Start (keV)	Middle (keV)	End (keV)
A0	-3.540	66.529	-0.238	0.060731	3.949430	12.131009
A1	-1.262	65.518	-0.186	0.026908	3.963552	12.169284
A2	-2.090	66.181	-0.273	0.039139	3.956777	12.264119
A3	-2.186	65.432	-0.215	0.041057	3.990546	12.273397
A4	-2.970	66.774	-0.245	0.051973	3.927410	12.089725
B0	-3.030	66.123	-0.181	0.053385	3.952595	12.034285
B1	-0.772	65.278	-0.246	0.019477	3.985723	12.360293
B2	-0.641	66.084	-0.237	0.017255	3.931424	12.170003
B3	-1.751	65.828	-0.218	0.034192	3.959848	12.193321
B4	-0.599	65.697	-0.204	0.016736	3.946548	12.166389

NOTE.—The gain equation is $y = A + Bx + Cx^2$, where x is the true line energy and y is the channel in which the line peaks.

noise ratio, such as provided by observations of the bright Earth (§ 5.4).

The resolution of a Si(Li) detector can be described by the relation $\sigma = [(F/\omega)E + \sigma_A^2]^{1/2}$ where F is the fano factor, ω is the mean energy necessary to create one electron-hole pair, and σ_A^2 is the variance due to the noise in the electronics (Fraser 1989). The Gaussian response widths were initially measured using photopeaks for $K\alpha$ and $K\beta$ and the escape peak for $K\alpha$ from preflight Fe^{55} and Ca^{41} calibration data (the photopeaks of K from Ca^{41} are at 3.31 and 3.59 keV). The calibration lines were modeled with a Gaussian (using a diagonal response matrix), and the results were fit with the relation $y = (Ax + B)^{1/2}$, where y is the Gaussian σ and x is the line energy in keV. The best-fit coefficients for each pixel are given in Table 4. Figure 3 shows the measured FWHM versus energy for the central A pixel. The FWHM resolution is ~ 155 eV at 5.9 keV in both central pixels and ~ 170 eV at 5.9 keV in the outer pixels. The in-flight resolution was determined to be the same as the preflight resolution for Fe^{55} .

3.3. Partial Charge Collection

Deviations from Gaussian response shapes in Si(Li) detectors have been extensively discussed in the literature (Shima et al. 1983; Campbell et al. 1985; Yacout, Gardner, & Verghese 1986; Inagaki, Shima, & Maezawa 1987). The intensity of the sum of the non-Gaussian-peak components correlates with the size of the detector dead layer, which is generally 0.1–0.2 μm thick (Shima et al. 1983; Joy 1985). The mean absorption depth of an X-ray, which can be written as $\lambda = 1/\rho$, where ρ is the linear absorption coefficient, ranges from ~ 0.1 μm at 0.4 keV to 14 μm at 1.8 keV (just before the Si edge). This is only slightly larger than the dead layer thickness. Therefore, soft X-rays are typically absorbed close to the front of the detector. Partial charge collection and charge trapping can occur when some of the charge carriers diffuse into the dead layer before being accelerated toward the anode by the applied bias voltage. Partial charge collection can also occur from the escape of Auger electrons or photoelectrons that are emitted near the boundary between the dead layer and the depletion region. The fraction of charge that is lost increases as a function of the ratio of the dead layer thickness to the mean absorption depth (D/λ) (Joy 1985; Shima et al. 1983). The partial charge fraction

TABLE 4
RESOLUTION COEFFICIENTS

Detector	A	B
A0	4.48940E-04	1.71804E-03
A1	4.65352E-04	2.13648E-03
A2	4.55287E-04	2.32979E-03
A3	4.71554E-04	2.08003E-03
A4	4.85625E-04	2.57638E-03
B0	5.61384E-04	1.23391E-03
B1	5.53610E-04	1.82161E-03
B2	5.28301E-04	2.01821E-03
B3	5.19983E-04	1.95085E-03
B4	4.95977E-04	2.12448E-03

NOTE.—The energy resolution (σ in keV) is given by $y = (Ax + B)^{1/2}$, where y is the Gaussian σ and x is the line energy in keV.

FIG. 3.—Plot of the measured Gaussian FWHM from preflight calibration data vs. energy for the central A detector pixel (A0). The points with the largest error bars were obtained from the $K\alpha$ escape peaks.

also exhibits a sharp jump at the silicon K edge where there is a large decrease in the mean absorption depth (Joy 1985; Inagaki et al. 1987).

Utilizing preflight calibration data, we modeled the partial charge in the detector as a step function (convolved with a Gaussian) starting at the energy of the incident X-ray and extending to zero energy. The shape is given by

$$S(E) = \frac{1}{2} \operatorname{erf} \left(\frac{E - E_c}{\sqrt{2}\sigma} \right). \quad (3)$$

After the mission, the magnitude of the step was adjusted to approximate the partial charge that was observed for the Crab Nebula as well as the oxygen fluorescence airglow line (§ 3.7). Figure 4 illustrates the current model for the response function in pixels B0 and B3, compared with potassium $K\alpha$ and $K\beta$ from Ca^{41} obtained from preflight calibration runs. The A0 data are not shown but are similar to the B0 data. Pixel B3 was chosen to illustrate the partial charge in the outer B pixels, which has a larger tail at less than 0.7 keV than the partial charge in the outer A pixels. Clearly, our step function model does not properly account for the shape of the partial charge distribution. First, a wing on the low-energy side of the main photopeak is visible in Figures 4a and 4b. However, since it amounts to less than 5% of the amplitude of the photopeak and the BBXRT signal-to-noise ratio is not sufficient to observe wings on emission lines from celestial sources, we have not included the wing in the response function. The partial charge distribution also rises toward low energies. The low-energy tail is clearly visible in the B detector when observing bright celestial sources such as the Crab Nebula (see § 3.5). However, we found from comparing the preflight calibration data (e.g., Fig. 4) with the Crab data that the relative magnitude of the low-energy tail as compared with the step function (eq. [3]) appears to be larger in the calibration data. Because of the uncertainties inherent in fitting the Crab to determine the magnitude of this tail for celestial sources, we have presently not included

FIG. 4.—Preflight calibration data fit with the present BBXRT response function (solid line): (a) potassium $K\alpha$ and $K\beta$ from Ca^{41} in pixel B0 and (b) potassium $K\alpha$ and $K\beta$ from Ca^{41} in pixel B3.

it in our response function. However, not including the tail causes difficulty in attempting to adjust the effective area curve at low energies (§ 3.7). The lack of a correct model of the partial charge distribution remains one of the largest uncertainties in the effective area calibration.

3.4. The Crab Nebula

Observations of the Crab Nebula (a standard X-ray calibration target) were made four times during the mission, twice approximately on axis and twice well off axis. Light curves of the day 3 observation in the A pixels are shown in Figure 5. The Crab Nebula was first observed for 2300 seconds at ~ 3.0 off axis, with the source flux highest in pixels A1 and B3. The position of the Crab on the detector during this time is illustrated in Figure 6. An attitude adjustment that began at 3.054 days MET placed the Crab in pixels A0 and B0. This observa-

tion is designated “on axis” for purposes of calibration, although the source was offset by about $1'$ toward pixel A3. The first half of the on-axis observation was performed during orbit night, while the second half was performed during orbit day (Fig. 5).

The Crab Nebula X-ray spectrum can be well described by a single absorbed power law, $N(E) \propto E^{-\Gamma} e^{-\sigma(E)N_H}$, over the 1–10 keV energy band (Seward 1992; Weaver 1993, and references therein). The photon index is well known, with the average value in the literature being $\Gamma = 2.1$. There is, however, some disagreement over the observed value of the hydrogen column density (N_H) along the line of sight to the Crab. The measured values for N_H are not all consistent, and the discrepancy is rather high in a few cases (see Seward 1992; Weaver 1993, Table 3.4; and references therein). The mean value of the column density from the literature is $N_H = 2.9 \pm 0.4 \times 10^{21} \text{ cm}^{-2}$.

FIG. 5.—Light curves of the Crab observation from the A detector pixels on day 3. The source pixel changes from pixel A1 to pixel A0 at 3.054 days MET.

FIG. 6.—BBXRT pixels superposed on an *Einstein Observatory* IPC image of the Crab Nebula. This represents the orientation of the detectors during the off-axis observation on day 3 (3.04–3.05 days MET). The A pixels are drawn with solid lines, and the B pixels are drawn with dotted lines. This figure illustrates the offset between the A and B detectors that is described in § 2.3.

Complexities in the Crab's spectral and spatial characteristics have been observed at both high and low energies. The spectrum flattens at high energies due to the contribution from the pulsar. This effect is $\sim 10\%$ at 10 keV (Toor & Seward 1977). At energies below 2 keV, the angular size of the Crab increases. This has been attributed to interstellar dust that causes low-energy photons to be scattered out of the central regions into a dust halo. The angular diameter of the halo is $8.3 E^{-1}$ arcmin and the fraction of the X-rays scattered into the halo is $0.066 E^{-2}$, where E is measured in keV (Schattenburg & Canizares 1986). Eleven percent of the total 0.5–3.5 keV flux measured with the *Einstein Observatory* IPC appears at a radius of greater than $1/6$ (Mauche & Gorenstein 1989).

Because the size of the BBXRT central pixel ($3/6$ diameter) is comparable to the extent of the Crab at medium energies ($2'$ diameter at 4 keV; $16'$ diameter at 0.5 keV), we expect to see a higher fraction of soft photons in the outer pixels than in the central pixels when the Crab is roughly centered in A0. Similarly, we expect to see relatively more soft flux in A0 when the Crab is $3/0$ off axis than when the Crab is roughly centered in A0. Figure 7 shows the ratio of the A0 spectrum when the Crab is off axis to the A0 spectrum when the Crab is on axis, normalized at ~ 2 keV. We do not find the expected increase in the flux ratio at low energies, although a decrease is observed in the ratio of the spectra at high energies due to the off-axis vignetting of the mirrors (§ 3.6 below). A deficiency of counts in the central pixels due to dust scattering is not required in the spectral fits either. When the Schattenburg & Canizares model of the dust-scattering halo is included in the fit to the on-axis A0 Crab spectrum, the column density decreases from 3×10^{21} to $2.7 \times 10^{21} \text{ cm}^{-2}$ (cross sections from Morrison & McCammon 1983) but the fit is not statistically improved. In addition, when an absorbed power-law model is fitted to spectra from the outer A pixels when the Crab is on axis, we find $N_{\text{H}} = 3 \times 10^{21} \text{ cm}^{-2}$, which is similar to N_{H} measured in A0. We conclude that any effects of the dust-scattering halo are less than the uncertainty in the hydrogen column to the Crab, so for simplicity we do not include a dust-scattering halo in our cali-

bration model. The effective areas for the two central pixels are refined based on fitting the Crab spectrum to an absorbed power law with $\Gamma = 2.10$ and a neutral hydrogen column density of $3.0 \times 10^{21} \text{ cm}^{-2}$.

3.5. Differences between Detectors

Fewer counts are observed in the B detector than in the A detector below about 2–3 keV for all detector elements. Figure 8 illustrates this effect for the Crab in the central pixels. During the mission it was thought that the decreased efficiency in B at low energies was due to the accumulation of ice on the surface of the detector. However, postflight calibrations performed at GSFC and the National Institute for Standards and Technology discredited the hypothesis that the B detector could be covered with ice because the relative deficiency of counts persists even after a deicing of the detectors. Also, the extra absorption is not likely due to excess Parylene in the B filter because the decreased efficiency occurs even at energies of 2 keV (Fig. 8). We therefore conclude that the B detector must be covered with a thicker gold surface contact layer than the A detector (§ 3.7 and Table 5).

Another difference between the two detectors is in the magnitude and the shape of the low-energy tail of the partial charge collection in the outer pixels. Figure 9 shows Crab spectra from the A1 and B3 pair of outer pixels when the Crab is on axis. Although between 0.7 and 2.0 keV B has fewer counts than A (due to the excess gold on the B detector), the B3 spectrum rises below 0.7 keV to meet the A1 spectrum. This is due to a large low-energy tail contribution to the partial charge in the outer B pixels, which is also present in the B detector preflight calibration data (Fig. 4) but not similarly observed in the outer A pixels.

3.6. The Mirror Areas and Flux Corrections

The density of the vacuum-deposited gold on the mirror surface is less than that of solid gold. This has the effect of reducing the reflectivity at high energies. However, we had no direct way of measuring the density of the gold on the mirrors. Hence, the effective gold density, $\rho_{\text{eff}} = C \rho_{\text{gold}}$, was treated as a free parameter in the effective area calculations. The on-axis mirror effective area curve was generated by ray tracing (Petre & Serlemitsos 1988) using a gold density fraction of $C = 0.87$, assumed to be the same for both telescopes. The value of $C = 0.87$ was derived from an early fit to the Crab before absorption due to the Ni mesh in front of the detector was included in the detector efficiency calculations. After a first-order correction for the Ni absorption was included, the original effective area curve gave a slope that was too steep for the on-axis Crab observation in A0. Since the high-energy efficiency of the telescope depends on the gold density, we were able to obtain a more reasonable slope of 2.1 by reducing C from 0.87 to 0.84.⁵ In A0, the 2–10 keV fit to the Crab after reducing the gold density fraction gave the expected values of $N_{\text{H}} = 3 \times 10^{21} \text{ cm}^{-2}$ and $\Gamma = 2.1$.

⁵ This flattening was done before a possible explanation was found for a “too steep” Crab slope. A steeper apparent slope in A0 can be caused by energy-dependent scattering of the mirrors (§ 3.8.3). This implies that the gold density fraction may actually be 0.87 and that we have overcorrected the effective area.

FIG. 7.—Ratio of off-axis to on-axis observations of the Crab Nebula in the central A pixel. The data were normalized at 2 keV. The “feature” at ~ 0.5 keV appears to be variable and is discussed in § 3.8.1.

FIG. 8.—Comparison between the A and B detector central pixels for the on-axis Crab observation.

The strongest feature in the Crab data is the gold M-edge complex due to absorption of X-rays by the mirrors. The energy of the main gold edge in the A system appears at the expected value of 2.22 keV (Figs. 8 and 9). However, the main edge appears at a higher energy of 2.25 keV in the B system, which indicates a difference between the A and B mirrors. It is not unreasonable that the energies of gold edges from the A and B mirrors differ slightly. In fact, experiments to study X-ray absorption fine structure allow the energy of the main absorption edge to be a free parameter (Lee et al. 1981). This is because there is an intrinsic uncertainty in determining the threshold energy of an absorption edge due to variations in the density of states near the Fermi energy that causes structure to be present within ± 10 eV of E_0 . Also, chemical-bonding effects can shift the apparent edge toward higher energies by up to 15 eV (Agarwal 1991; Lee et al. 1981).

To accurately fit the Crab between 0.5 and 0.8 keV it was necessary to include features in the effective area that can be interpreted physically as gold N edges at energies of 0.546, 0.643, and 0.762 keV. The best-fit values for the absorption depths of the edges for each mirror-plus-detector combination were obtained using central-pixel Crab data along with the best-fit detector absorption parameters (see § 3.7 and Table 5). The absorption depths of the edges are as follows: $\tau = 0.3, 0.18$, and 0.12, respectively, for A and 0.66, 0.12, and 0.16 for B, with a typical error of 0.04. The relative edge depths are roughly what we might expect to observe for the A system, and the depths of the 0.643 and 0.762 keV edges in the B system are not significantly different from those in A. However, the 0.546 keV edge depth in B is twice that in A. The stronger “edge” in B can clearly be seen in the Crab data (Fig. 8); however, the absorption depth we measure may not be physical because of the various uncertainties in adjusting the effective area curve for B at low energies (§ 3.7).

Two vignetting corrections are currently included in the standard BBXRT response matrix. First, the effective area curve is normalized by 62% under the assumption that one is

analyzing data from the A0 pixel for an on-axis source. This correction factor accounts for 38% of the source counts being lost, primarily to the mask and the outer pixels (§ 2.2), and provides accurate fluxes for sources that are more or less centered in A0 (§ 4). Second, for off-axis sources, energy-dependent vignetting corrections to the effective area are included in the response; these were obtained by modeling the throughput of the mirrors as a function of off-axis angle using ray-tracing techniques (Petre & Serlemitsos 1985). The results of the ray tracing for off-axis observations are presented in Figure 10, which shows the ratio of off-axis to on-axis effective areas as a function of energy for various off-axis angles. The current ray-tracing calculations have been performed for point sources only.

A third correction that has *not* been included in the response matrix accounts for the (often significant) loss of photons for sources observed off axis due to the presence of the masks between the detector elements. If a source happens to sit on a mask, up to 50% of the photons reaching the focal plane can be lost. As an illustration of the potential severity of the problem, the distribution of photons in the focal plane for a point source observed in three different locations is shown in Figure 11. Here, the azimuthal angle Φ is arbitrarily measured with respect to the edge of the outer pixel nearest the source position and increases toward the center of that pixel (Fig. 11, *top left*). Due to the symmetry of the outer pixels, Φ ranges from 0° to 45° . Case *a* illustrates the distribution of photons for a point source that is directly on axis. For a source that is located $4'$ off axis directly on the mask (case *b*), the total collection efficiency is cut by half. However, in case *c*, where the source is off axis but centered in an outer pixel ($\Phi = 45^\circ$) the total collection efficiency is higher than in case *a* due to the larger size of the outer pixels. We have used ray-tracing techniques to calculate the fraction of counts lost to the mask for a multitude of source positions. Figure 12 provides the flux-correction factor to be used for off-axis observations for sources having off-axis angles

FIG. 9.—Comparison between the A1 and B3 outer pixels when the Crab Nebula is roughly centered in the detector. The B3 data are designated with triangles.

FIG. 10.—Ratio of off-axis to on-axis effective area as a function of energy for various off-axis angles (in arcminutes).

(Θ) ranging from $0'$ to $8'$ and azimuthal angles of $\Phi = 0^\circ$, 22.5° , and 45° .

To determine the flux for an off-axis point source, Θ and Φ must be known. If an aspect solution is available, the R.A. and decl. offsets and the roll angle (Table 1) provide both Θ and Φ . Otherwise, Θ and Φ are estimated by utilizing the available ray-tracing program. Once Θ and Φ are determined, Figure 12 gives the appropriate correction to the fluxes derived with the current BBXRT response matrix. For example, for a point source having $\Theta = 5'$ and $\Phi = 45^\circ$, the flux correction factor for the A detector pixel in which the source is located (the “source pixel”; labeled as “pixel 1” in Figs. 11 and 12) is 1.23. The flux correction factor for each of the adjoining or “nonsource” outer pixels (labeled as “pixel 2” and “pixel 4” in Figs. 11 and 12) is ~ 0.02 . To derive the flux of the source, divide the apparent flux (found from the spectral fit) by the flux correction factor for that pixel.

3.7. The Detector Efficiency

The detector efficiency was originally calculated including the values for Parylene N, Al, Si, and Au that had been specified to the manufacturers for the parylene and aluminum in the UV filter, the silicon dead layer in the detector, and the gold in the surface contacts (listed in Table 5). However, using these values in the response matrix provided a poor fit to the Crab, giving a reduced χ^2 of about 2.5 in A0. Therefore, the current A0 and B0 pixel effective area curves were generated by allowing the optical depths of the various sources of absorption within and above the detectors to be free parameters in the fits to the Crab. Details of the procedure are given by Weaver (1993). For both detectors, we assumed that gold and aluminum absorption was uniform across the detector, while the parylene and silicon absorption was allowed to vary for each pixel. Although the Crab Nebula was not observed in all pixels, other bright sources that were observed at least twice, both on and off axis, were available for calibration of the outer pixels. The targets used to calibrate the outer pixels and to provide

consistency checks between pixels are listed in Table 6. The effective area curves of the outer A pixels were calculated by fitting spectra from each pixel simultaneously with an A0 spectrum of the same source and varying the effective area to give the best fit. A similar but more rigorous procedure was adopted for the outer B pixels because of the known uncertainty in the partial charge modeling. The magnitude of the partial charge was initially fixed by examining the shape of the low-energy side of the oxygen fluorescence airglow line. The effective area curves were then calculated by fitting spectra from each pixel simultaneously with a B0 spectrum of the same source and varying the effective area to give the best fit.

Some of the best-fit absorption values turn out to be unphysical (e.g., negative silicon) and so they will be discussed as “absorption parameters,” which allow an improved fit to the Crab data. The best-fit detector absorption parameters for each pixel are given in Table 5. The values in columns (2)–(7) are almost identical for all of the A pixels, while there is much less consistency between the best-fit values for the B pixels. The B detector requires a partial covering of gold described by

$$\text{abs} = \exp(-\text{Gold1}z - \text{Gold2}z^2), \quad (4)$$

FIG. 11.—Distribution of photons in the focal plane for a point source observed at different positions: (a) on axis (in pixel 0; $\Theta = 0'$, $\Phi = 0^\circ$), (b) $4'$ off axis sitting directly on the mask ($\Phi = 0^\circ$; between pixels 1 and 4), and (c) centered in an outer pixel (pixel 1; $\Theta = 6'$, $\Phi = 45^\circ$). In the upper left corner is a schematic diagram of the A detector; the pixels are arbitrarily numbered for purposes of cross-referencing this figure with Fig. 12. The pixel numbers assigned here should not be confused with the true designation of pixels as A0, A1, A2, A3, and A4.

FIG. 12.—Flux-correction factor as a function of off-axis angle for three different azimuthal angles: (a) $\Phi = 0^\circ$, (b) $\Phi = 22.5^\circ$, and (c) $\Phi = 45^\circ$. The pixel numbers correspond to those in the upper left panel in Fig. 11, where the “source” pixel is typically pixel 1, pixel 0 is the central pixel, and pixels 2 and 3 are generally farthest from the source position.

where Gold1 is the number of clumps times thickness, Gold2 is the number of clumps times thickness squared, and z is defined as the energy-dependent absorption cross section. This is not a physical model, but is merely a way of adding a free parameter.

The negative values that we measured for the thickness of the Si dead layer (Table 5, col. [5]) are physically meaningless. This implies that we do not understand one or more of the following: (1) the effects of the partial charge collection around the silicon edge, (2) the thickness of the silicon dead layer in the detector, (3) the importance of the low-energy partial charge wing discussed earlier (§ 3.3), or (4) the silicon-absorbing column to the Crab. Negative silicon also affects the best-fit parylene absorption, causing it to be too high, because it compensates (at low energies) for the decreased silicon. The “silicon problem” is worse in the B detector. However, this primarily occurs because the present partial charge model is

not correct (see Fig. 4), which affects the region of the Crab model around the Si K edge (Weaver 1993).

After the absorption parameters were adjusted, we found that the effective area curve still underpredicted the Crab data at greater than 6 keV. This high-energy tail was a 20% effect in both A0 and B0 at 10 keV, more than the 10% flattening expected due to the presence of the pulsar. The excess of photons in the Crab at high energies has been corrected by multiplying the effective area by a relation of the form $R = mE + b$ above 5.2 keV, where m is 0.0429 and 0.055 for A and B, respectively, and b is 0.772 and 0.708 for A and B. There is currently no physical basis for this correction.

3.8. The Effective Area Curve

3.8.1. On-Axis Observations

Figure 13 shows the current on-axis mirror-plus-detector effective area curves for A0 and B0. Figure 14a illustrates the best power-law fit to the on-axis A0 Crab observation (580 counts s^{-1} in A0; data from 3.0569–3.068 days MET), which results in $\Gamma = 2.1$ and $N_H = 3 \times 10^{21} \text{ cm}^{-2}$. The residuals from the fit are shown in Figure 14b. Figure 15a shows the best power-law fit to the on-axis B0 Crab observation (from 3.0569–3.068 days MET), which also results in $\Gamma = 2.1$ and $N_H = 3 \times 10^{21} \text{ cm}^{-2}$. The residuals from the fit are shown in Figure 15b. At the present time, the effective area is understood at the 5% level in A0 with up to 10% residuals at very low energies (< 0.6 keV). The area is also understood at the 5%–10% level in B0 over 0.6–9 keV. However, residuals to the Crab in B0 appear both below 0.6 keV and above 9 keV at the 10%–15% level. The $\sim 10\%$ residuals above 9 keV appear to be caused by incomplete modeling of the 8.3 keV nickel edge. There also appears to be a larger mismatch to the Al, Si, and Au edges in B0 than in A0, and there is a narrow feature present at 1.38 keV in B0. This feature is at worst a 10% residual, and less than 10 eV equivalent width when fit with a Gaussian. In addition, a less than 5% “bump” in the residuals still exists around 7.5 keV in both A and B.

The worst residuals in both detectors are at ~ 0.5 keV. When the on-axis Crab data are split into night (3.057–3.062 days

TABLE 5
BEST-FIT DETECTOR ABSORPTION THICKNESS

Detector (1)	Step ^a (2)	Parylene (Å) (3)	Aluminum (Å) (4)	Silicon (Å) (5)	Gold1 (Å) (6)	Gold2 (Å) (7)
Specification	...	4000	1500	900	200	...
A0	3.40E-05	8150	1625	-100	126	0.0
A1	3.40E-05	8150	1625	-100	126	0.0
A2	3.40E-05	8150	1625	-100	126	0.0
A3	3.40E-05	8150	1625	-100	126	0.0
A4	7.50E-05	8150	1625	-100	126	0.0
B0	4.40E-05	11000	1900	-1000	212	44944
B1	6.00E-05	4400	1900	-2650	212	44944
B2	9.00E-05	5500	1900	-2000	212	44944
B3	9.00E-05	11000	1900	-3200	212	44944
B4	7.00E-05	8250	1990	-3300	212	44944

^a Step refers to $S(E)$, the amount of partial change (eq. [3]) included in the response function.

MET) and day (3.062–3.068 days MET) there is an indication that the low-energy residuals change with time, ranging from a 5% to a 15% effect. In B0, they are almost absent in the background-subtracted daytime data (Fig. 16a) but are strong in the nighttime data (Fig. 16b). This effect is reversed in the A0 detector, with the residuals being stronger in the daytime data. There is no correlation between the size of the residuals and the detector guard rate (§ 5.1), the rate of light-emitting diode (LED) firings (§ 5.1), the Earth angle (§ 5), or background subtraction. An alternative explanation would be that the gain or resolution at low energies may have changed with time. The magnitude of the residuals can be measured as follows: fitting the positive ~ 0.5 keV feature with a narrow Gaussian ($E = 0.41$ keV) gives an equivalent width of less than 140 eV in A0 and less than 220 eV in B0. Fitting the negative feature gives an energy of 0.52 keV (a slightly lower energy than an oxygen edge at 0.53 keV). Fitting with a notch (width 0.03 keV) gives a covering fraction for the notch of less than 0.4 for A0 and less than 0.65 for B0.

Figure 17 shows the confidence contours for N_H versus Γ derived from all 10 pixels when the Crab is approximately on axis. First, it can be seen that the 90% confidence contours for A0 and B0 overlap, indicating that the two central pixels (the source pixels) give consistent results for the on-axis Crab observation. Second, this figure illustrates that for the outer pixels (the nonsource pixels), the systematic uncertainties that remain ($\Delta\Gamma = 0.2$) are 2–3 times greater than the statistical uncertainties in fitting the Crab. This systematic uncertainty measured in the outer pixels may be caused by fact that we have

not correctly accounted for the energy dependence in the mirror PSF (§ 3.8.3 below).

3.8.2. Off-Axis Observations (Source Pixel)

Table 7 lists the lowest available channels and the lowest reliable channels for all pixels, along with the corresponding channel energies. A0, B0, and the outer A pixels (A1, A2, and A3) are reliable down to their lowest usable energies, determined by the setting of the detector noise threshold. The A4 pixel is particularly noisy and so is only reliable down to about 0.7 keV. Also, because of the large correction and uncertainty in modeling the partial charge, the outer B pixels are reliable only down to 0.5–0.7 keV. The less than 0.7 keV excess seen in the Crab data in the outer B pixels (Fig. 9) has not been removed because it is not possible with our present modeling of the partial charge with a step function. A full understanding of the magnitude and shape of the partial charge is needed to utilize the outer B pixels at low energies.

FIG. 13.—The on-axis mirror-plus-detector A0 and B0 effective area curves.

TABLE 6
OUTER-PIXEL CALIBRATION SOURCES

Pixels	Primary	Secondary	Consistency check
A1 and B3	Crab	PKS 2155-304	Perseus
A2 and B4	Perseus	Capella	PKS 2155-304
A3 and B1	Cygnus X-2	Perseus	PKS 2155-304
A4 and B2	Cygnus X-1	Perseus	Earthglow

FIG. 14a

FIG. 14b

FIG. 14.—(a) Plot of the on-axis A0 Crab data and best-fit model: $\Gamma = 2.115$, $N_H = 3.04 \times 10^{21} \text{ cm}^{-2}$. For this fit, $\chi^2_\nu = 1.4$. (b) Ratio of the data to the model.

The confidence contours for N_H versus Γ for all pixels when the Crab is 3.0 off axis are shown in Figure 18. In this case, the source pixels are A1 and B3. The index measured for A1 ($\Gamma = 2.16$) is steep and is inconsistent with the index measured for B3 ($\Gamma = 2.09$). This represents the largest discrepancy still remaining between pairs of source pixels ($\Delta\Gamma \sim 0.10$), although this should be an observable problem only for bright sources ($\geq 10 \text{ counts s}^{-1}$) with good statistics. The remaining discrepancy between A1 and B3 is smaller than the general systematic uncertainties observed between outer, nonsource pixels when the Crab is on axis (Fig. 17).

3.8.3. On- and Off-Axis Observations (Nonsource Pixels)

For a point source observed with BBXRT, there are still large systematic residuals when attempting to use data that are

not from the source pixel (i.e., from a nonsource pixel). During the on-axis observation, the Crab was actually offset by about $1'$ toward A3 and B1 (§ 3.4). From Figure 17, it can be seen that for this observation, for 5 out of 6 of the pixels *other* than A0, B0, A3, and B1 (i.e., those pixels in which the majority of the Crab flux is coming from a region greater than $5'$ away from the core of the PSF), the spectra tend to be flatter. The effect is even more obvious during the off-axis Crab observation (Fig. 18). In this case, the source pixels are A1/B3 and A0/B0, while A3/B1 are the furthest from the source in detector coordinates. Clearly, the measured photon indices become much flatter with increasing angular distance from the Crab.

The flattening in the Crab spectrum observed in nonsource pixels is due to the increased presence of a high-energy tail when we examine data obtained from a greater than $5'$ – $6'$ radius away from the center of the source in detector coordinates.

FIG. 15a

FIG. 15b

FIG. 15.—(a) Plot of the on-axis B0 Crab data and best-fit model: $\Gamma = 2.12$, $N_H = 3.08 \times 10^{21} \text{ cm}^{-2}$. For this fit, $\chi^2_\nu = 1.38$. (b) Ratio of the data to the model.

FIG. 16.—Plot of the 0.3–1.4 keV ratio of the unbinned B0 Crab spectra to the best-fit power-law model for the on-axis observation divided into (a) day and (b) night.

This flattening can be seen in power-law fits to data from the outer pixels when the Crab is observed approximately on axis. Figure 19 shows a plot of the ratio of the A2 and B4 Crab spectra to an absorbed power-law model having an index of $\Gamma = 2.1$. In this case, the best-fit N_H is the “expected” value of $3 \times 10^{21} \text{ cm}^{-2}$. A tail at high energies (which is a 20% effect) is observed in the ratio of the data to the model.

One explanation for the high-energy tail seen in the non-source pixels is an energy dependence of the mirror point-response function for large radii, in the sense that higher energy X-rays are scattered into larger angles. Although measurements appropriate to test for an energy dependence are not available for the BBXRT mirrors, this effect has been observed for similar mirrors which are presently flying on *ASCA* (H. Kunieda and the *ASCA* calibration team 1993, private communication). Preliminary measurements of the *ASCA* mirrors indicate that 7% of the flux at 2 keV, 15% of the flux at 5 keV, and 17% of the flux at 8 keV is scattered from the core of the mirror PSF into a greater than $6'$ radius (thus extending the wings of the PSF for higher energies). This energy-depen-

FIG. 17.—Confidence contours for N_H vs. Γ for all pixels when the Crab is on axis. The contours shown are 68%, 90%, and 99%. Contours for the A pixels are solid lines.

dent scattering, due to the residual roughness of the mirror foils, has exactly the right magnitude to explain the high-energy tail observed in the outer-pixel BBXRT data when the Crab is centered (Fig. 19), although off-axis measurements of the Crab indicate that this tail is an even larger effect than expected for a simple energy dependence in the PSF.

The BBXRT mirror effective area curve was generated for the entire focal plane. However, we used only the A0 data (essentially from the beam core) to modify the effective area to fit the Crab. If scattering out of the beam core is energy dependent (which is highly probable given the *ASCA* results), then a larger fraction of high-energy photons than low-energy photons are scattered out of the core. This means that the measured slope of the Crab when using only central pixel data should be “too steep.” We may have inadvertently corrected for this steepening by altering the mirror gold density fraction from 0.87 to 0.84 (although the original spectral steepening was less than a 5% effect, see § 3.6). It is therefore likely that our calibration contains a systematic error in the sense that measured spectral slopes will be too flat by about 5%–10% (in

TABLE 7
RELIABILITY OF LOWEST ENERGY EFFECTIVE AREA

Pixel	Lowest Usable Channel	Energy (keV)	Lowest Reliable Channel	Energy (keV)
A0	16	0.29	16	0.29
A1	26	0.41	26	0.41
A2	26	0.42	26	0.42
A3	27	0.44	27	0.44
A4	25	0.41	43	0.70
B0	17	0.30	17	0.30
B1	27	0.42	39	0.60
B2	28	0.43	34	0.52
B3	28	0.45	34	0.54
B4	29	0.44	45	0.69

FIG. 18.—Confidence contours for N_H vs. Γ for all pixels when the Crab is 3.0 off axis. The box delineates the region shown in Fig. 17. The contours shown are 68%, 90%, and 99%. Contours for the A pixels are solid lines.

$\Delta\Gamma$) when using data from a source pixel, whether the source is observed on or off axis. However, this small effect should only be noticeable for sources having count rates greater than ~ 10 counts s^{-1} . For data from a nonsource pixel, the systematic flattening at high energies, thought to be caused by the energy dependence in the PSF, can easily dominate statistical uncertainties for most point sources (Figs. 18 and 19).

4. FLUX CALIBRATION

To determine the normalization of the BBXRT effective area curve using the Crab Nebula, corrections must be applied to the observed count rate because some of the X-ray events are not recorded in the telemetry. There are four reasons for this, two of which are dead-time effects. First, if an event occurs within $\sim 100 \mu s$ of a previous event in the same pixel, then it is lost and the earlier event is flagged. Second, the telemetry is only able to hold 252 events per frame (2016 events s^{-1}) and so once the buffer is full, additional events will be lost before the start of the next telemetry frame. Third, events in the same pixel which occur very close together (within $20 \mu s$) may not be sensed as different events in the electronics. This causes a pile-up of pulse heights that can make multiple events appear as one event with a higher energy and may affect the spectrum for large count rates. Finally, events may be flagged with one of the quality flags: guard, large event, pixel-to-pixel, or LED (§ 5.1). When extracting spectra, we normally exclude any flagged events.

The effects of dead time (assumed to be energy independent), flagging, and pulse pile-up were examined using all of the events in the telemetry for a 1 s interval for the on-axis A0 Crab observation at 3.056 days ($3^d 4839^s$). The observed count rate in the Crab spectrum is the true count rate corrected for dead-time effects ($c_d = 0.855$), the flagging ratio ($c_f = 0.79$), and the ratio of the instantaneous to the average count rate ($c_{av} = 0.96$). This gives

$$R_{\text{obs}}(\text{spectrum}) = c_d c_f c_{av} R_{\text{true}} = 0.648 R_{\text{true}}. \quad (5)$$

An absorbed power-law fit to the on-axis Crab observation in A0 gives a normalization of 6.16 ± 0.04 photons $s^{-1} \text{ keV}^{-1} \text{ cm}^{-2}$ at 1 keV (90% confidence errors). After applying the above correction, this results in

$$N(E) = 9.51 E^{-2.11} e^{-\sigma(E)N_H}, \quad (6)$$

where $N(E)$ is given in photons $s^{-1} \text{ keV}^{-1} \text{ cm}^{-2}$. The value of 9.51 that we find for the derived normalization at 1 keV agrees well with the normalizations measured by previous experiments (Toor & Seward 1974; Burrows 1982; Turner et al. 1989) and indicates that our derived Crab flux is accurate to within $\sim 15\%$.

The flux calibration described above only applies to sources observed on axis in the A detector. Since we have not included the B detector offset in the effective area, only data from the A detector should be used to determine absolute source fluxes. We have also not included the effects of the mask in the effective area calculation. To account for the mask, one must apply a flux correction factor (see § 3.6 and Fig. 12).

5. THE DETECTOR BACKGROUND

There are four major contributions to the BBXRT detector background: internal background, particles, events from the cosmic or diffuse X-ray background (DXRB), and X-ray contamination at low energies from solar radiation scattered off Earth's atmosphere. This "Earthglow" is the dominant low-energy component for daytime observations, and its intensity correlates with the "Earth angle," defined as the angle between the telescope pointing direction and the direction of the center of the Earth. During nighttime observations, the instrumental background and the DXRB contribute equally at low energies.

5.1. Background Rejection Techniques

Five anticoincidence techniques were used for BBXRT background rejection. Any of the following conditions caused

FIG. 19.—Ratio of Crab data from A2 and B4 to a power-law model when the Crab is centered in A0. In this case, Γ is fixed to be 2.1 and the best-fit value of N_H is $3.0 \times 10^{21} \text{ cm}^{-2}$.

a detected event to be flagged as a “bad” event and not analyzed. First, pulse-pulse anticoincidence caused an event to be flagged when a simultaneous event ($<120\ \mu\text{s}$) was detected in the same pixel. Second, bad pulse heights due to splitting of events near pixel boundaries were measured by pixel-pixel anticoincidence, which worked mostly for large events ($\geq 10\ \text{keV}$). Third, very-large-event anticoincidence flagged an event that deposited a charge larger than that expected for a $14\ \text{keV}$ X-ray. These often triggered pulses in adjacent pixels. Fourth, events were flagged when the plastic scintillator guard was triggered simultaneously ($<150\ \mu\text{s}$). A housekeeping parameter called the “guard rate” measured the rate of particle interactions with the guard. Finally, events were flagged when simultaneous firing of the LED opto-feedback circuits occurred ($<1\ \text{ms}$).

5.2. The Non-X-Ray Background

The non-X-ray detector background is made up of electronic noise, microphonics, and particle events. Electronic noise is forced to be a small effect by setting the discriminator thresholds above $\sim 0.3\text{--}0.5\ \text{keV}$, the level at which it begins to contribute appreciably (§ 2.1). Microphonics are measured by the use of accelerometer data and are different from the noise associated with the ordinary detector leakage current (responsible for σ_A^2 described in § 3.2). Microphonics can be a major contribution at low energies (less than $0.8\ \text{keV}$). They are produced by changes in capacitance at the charge collection point of the preamplifier front-end junction field effect transistor when mechanical vibration of the rigid high-voltage lead within the cryostat is induced by external motions. Bursts of microphonics events typically last about $2\ \text{ms}$, occur once every $10\ \text{s}$, and contain up to 5 events spread over various pixels within a given detector. During data extraction, microphonics events can be eliminated for weak sources.

Particle events are the primary source of the non-X-ray background. At the end of the mission (8.3–8.8 days MET), several hours of data were obtained with the instrument covers closed to measure the non-X-ray background. During this time, the instrument was not passing through the South Atlantic Anomaly (SAA). Figure 20*a* shows the co-added non-X-ray background count rates with microphonics removed for the four outer A pixels versus time. The data are grouped into $200\ \text{s}$ bins and range over channels 30–511 ($0.5\text{--}12\ \text{keV}$). A similar plot for the B detector outer pixels is shown in Figure 20*b*. The guard rate, which measures the rate of particle interactions with the plastic scintillator surrounding most of the detector, is plotted in Figure 20*c*. The guard rate is also averaged over $200\ \text{s}$ bins and ranges from ~ 800 to 2000 per $8\ \text{s}$ housekeeping frame, typical of periods outside the SAA. It can be seen that the non-X-ray background event rate clearly follows the guard rate.

The outer-pixel non-SAA count rates for the non-X-ray background are plotted against the associated guard rate in Figures 21*a* and 21*b*. A correlation is clearly present, and it is approximately linear for guard rates greater than about 1000 and less than about 2000 . This correlation allows the non-X-ray component of the background to be easily predicted for a known guard rate. Below a guard rate of 1000 , the non-X-ray background reaches a lower threshold at about 0.15 and 0.18

FIG. 20.—Non-X-ray background from closed-cover observations on day 8 of the mission as a function of time: (a) count rate in channels 30–511 for the A1–A4 pixels, (b) count rate in channels 30–511 for the B1–B4 pixels, and (c) detector A guard rate (defined in the text). The data have been accumulated in $200\ \text{s}$ time bins.

counts s^{-1} in the summed outer A pixels and B pixels, respectively. The magnitude of the non-X-ray background (excluding microphonics) is $1.5 \times 10^{-3}\ \text{counts keV}^{-1}\ \text{s}^{-1}$ in each central pixel and $\sim 8 \times 10^{-3}\ \text{counts keV}^{-1}\ \text{s}^{-1}$ in each outer pixel, with the exception of A4 which has a very strong non-X-ray background component below $0.7\ \text{keV}$. The non-X-ray background in the central pixels is very flat between 0.4 and $11.0\ \text{keV}$ (Γ is approximately -0.2) and rises below $0.4\ \text{keV}$. Illustrations of the slightly more complex shape of the non-X-ray background in the outer pixels can be found in Weaver (1993).

5.3. The Diffuse X-Ray Background during Orbit Night

For nighttime source observations and Earth angles greater than 90° , the external X-ray background is due solely to the DXRB. For a guard rate of ~ 1000 , the count rate in the DXRB is approximately equal to the non-X-ray background count rate over $0.4\text{--}0.6\ \text{keV}$ and can be half the non-X-ray background count rate over $0.6\text{--}1.0\ \text{keV}$. However, the DXRB flux is less than 10% of the non-X-ray background at energies greater than $2\ \text{keV}$. The DXRB spectrum observed with BBXRT is presented by Jahoda et al. (1992) and will not be discussed further here. The diffuse background count rate remains roughly the same for all observations. This is because BBXRT is not particularly sensitive to spatial fluctuations in the DXRB due to short integration times.

5.4. The Atmosphere and the X-Ray–Bright Earth

The shuttle’s orbit places it in Earth’s upper atmosphere at an altitude of $\sim 200\ \text{km}$. Because low-energy X-rays are absorbed and scattered at such altitudes, it is important to have an accurate understanding of the composition and ionization state of the atmosphere. At $200\ \text{km}$, N_2 and O mainly constitute the atmosphere (Jones 1964; Mitra 1952; Zombeck 1990), and the ratio of O to N_2 is approximately 1:1 (Zombeck

FIG. 21.—Non-X-ray background count rate vs. the A detector guard rate for (a) all outer A pixels, channels 30–511, and (b) all outer B pixels, channels 30–511.

1990). In addition, the upper atmosphere below 700 km can be treated as neutral because at no time do the ions exceed their corresponding neutral species by more than 1% (Jones 1964).

BBXRT suffers from a large amount of low-energy (0.3–1.0 keV) contamination during “day-side” observations. This contribution to the X-ray background occurs when X-ray photons from the solar corona are scattered by Earth’s upper atmosphere. The relevant processes involved are Thomson scattering and fluorescent scattering. Thomson scattering dominates for energies greater than ~ 0.6 keV. By modeling the radiative transfer of X-rays through the Earth’s atmosphere, Snowden & Freyberg (1993) and Fink, Schmitt, & Harnden (1988) have determined that observed X-ray “bright Earth” light curves and spectra (from *ROSAT* and the *Einstein* IPC) can be predicted from a knowledge of the angle between the pointing direction of the telescope and the direction of Earth as well as the telescope-Earth-Sun angle.

BBXRT encountered two “states” of bright Earth emission: an “active” state when the Sun was flaring and a “quiet” state when the Sun was more or less quiescent. During the active state, when the Sun emits higher energy photons, emission lines of Mg, Si, and Ar are observed as well as a strong thermal continuum and Fe L emission. Fortunately, no flares occurred during daytime source observations. During the quiet state, the BBXRT spectrum is dominated by a weaker thermal continuum and scattered Fe L emission as well as O and N₂ fluorescence lines, and the observed intensity depends on the Earth angle. Spectra of the bright Earth for two ranges of Earth angles during the solar quiet state are shown in Figure 22. The Earth angle range of 70°–80° corresponds to looking directly at Earth’s limb ($\sim 76^\circ$ at 200 km). Between 90° and 100°, the spectrum is dominated by O fluorescence and is typical of what is seen during a daytime source observation. Figure 22 also illustrates how the Thomson-scattered continuum dies away for larger Earth angles.

We have investigated how the less than 2 keV bright Earth count rate correlates with Earth angle. Figure 23 shows the

FIG. 22.—Quiescent solar scattered spectra for Earth angle ranges of 70°–80° and 90°–100°. Data are from pixel A0.

change in count rate versus the Earth angle in three channel ranges: 27–42 (0.5–0.6 keV), 45–80 (0.6–1.0 keV), and 80–120 (1.0–2.0 keV). The channel range 27–42 emphasizes the oxygen line. The oxygen line is brightest at Earth’s limb (between 70°–80°), and there is a large drop in the count rate above 80°, although oxygen contamination persists up to 150°. Channels 45–80 emphasize the change in the Fe L count rate with distance from Earth’s limb. There is once again a rapid drop above 80° with significant counts in the Fe L complex even at an angle of 100°. For higher energies (channels 80–120) the same drop in count rate above 70°–80° occurs; for Earth angles larger than 80°, there is essentially no contribution to the background from energies greater than 1.2 keV. For Earth angles between 80° and 100°, the best description of the

FIG. 23.—Change in daytime background count rate in pixel A2 with Earth angle for three channel ranges: channels 27–42 (0.5–0.6 keV), channels 45–80 (0.6–1.0 keV), and channels 80–120 (1.0–2.0 keV). The non-X-ray background component has been subtracted.

bright Earth spectrum is a Raymond-Smith plasma continuum with $kT \sim 0.43$ and ~ 0.1 solar abundance, along with nitrogen and oxygen fluorescence lines.

6. BACKGROUND SUBTRACTION

The non-X-ray component of the background can be easily predicted as follows. First, the average guard rate during the source observation (the “source guard rate” [SGR]) is determined (Table 1). Second, the count rate of the non-X-ray background, which has a mean guard rate (MGR) of 1259, is scaled using the ratio of the MGR to the SGR to match the count rate that is predicted from the linear relation shown in Figure 21. Finally, the scaled non-X-ray background is subtracted from the source data. The non-X-ray background reaches a lower threshold at a guard rate of 1000 and should not be scaled below this value. The background subtraction procedure discussed here only applies to observations out of the SAA with an average accumulated guard rate of $\lesssim 1400$.

At present, the nighttime diffuse background has only been examined for Earth angles greater than 90° . There is no evidence for oxygen fluorescence from the Earth’s atmosphere above an Earth angle of 90° in the BBXRT data. Creating an appropriate background for an observation obtained during orbit night consists of adding two background files together. These are (1) a DXRB spectrum which has its non-X-ray background already subtracted and (2) the scaled non-X-ray detector background as described above.

The bright Earth count rate remains constant for guard rates of 800–1800 within a given range of Earth angles, in contrast to the linear correlation seen between count rate and guard rate for the non-X-ray detector background. A combined “best” background spectrum for a daytime observation consists of (1) the daytime background (which contains scattered light plus the DXRB spectrum) accumulated for the average Earth angle of the source observation, minus its non-X-ray background, plus (2) the non-X-ray detector background that has been scaled as described above. These can be added together to form one daytime background spectrum.

The adopted background subtraction algorithm is given below. In this algorithm, BG_N is the nighttime (diffuse only) background, BG_I is the non-X-ray background, $BG_D(EA)$ is the daytime (diffuse plus scattered) background as a function of Earth angle (usually given in degrees), NGR and DGR are the average guard rates of the nighttime and daytime backgrounds, respectively, and SGR is the average guard rate during the source observation.

BBXRT background subtraction algorithm:
Orbit night:

$$\begin{aligned} \text{Data} - [BG_N - BG_I(\text{scaled using NGR})] \\ - BG_I(\text{scaled using SGR}) ; \end{aligned}$$

Orbit day:

$$\begin{aligned} \text{Data} - [BG_D(EA) - BG_I(\text{scaled using DGR})] \\ - BG_I(\text{scaled using SGR}) . \end{aligned}$$

The fact that BBXRT has five detector elements makes the estimation of the simultaneous background fairly straightforward for weak point sources observed on axis. In this case, the simultaneous outer-pixel data provide a direct estimate of the background during the observation.

7. REMAINING SYSTEMATIC UNCERTAINTIES

We have presented the most up-to-date calibration of Goddard’s BBXRT. We currently understand the effective area curve at the 5%–10% level over 0.7–10 keV and at the 10%–15% level below 0.7 keV for data from a source pixel for both on- and off-axis observations of point sources. It is hoped that the techniques presented here are useful for the calibration of other present and future solid-state X-ray detectors. The calibration of the BBXRT detectors proved to be difficult because the problems encountered during the mission did not allow us to carry out our full calibration program. In fact, few adequate calibration targets were observed. Further refinements of the effective area will have to rely on postflight ground calibration measurements. A summary of the remaining calibration uncertainties and systematics, as fully explained in this paper, are listed below.

1. Our partial charge model does not properly account for the low energy (<0.7 keV) shape of the partial charge distribution. This mainly affects the B detector and causes data from less than 0.6–0.7 keV in B1, B2, B3, and B4 to be unusable.
2. A high-energy excess still exists in the B0 pixel above 9 keV (an $\sim 10\%$ effect). This is most likely due to incorrect modeling of the Ni edge at 8.3 keV.
3. Low-energy residuals in the Crab data are seen. These may vary with time and are a 5%–15% effect below 0.6 keV.
4. Residuals still remain around the Al, Si, and Au edges due to a mismatch of our model to the Crab data (5% effect).
5. Because we have not accounted for energy-dependent scattering out of the core of the mirror PSF, there is likely a systematic error for on-axis sources that causes the 2–10 keV slopes in A0 and B0 to be too flat by about 5%–10%. This should only be significant for bright targets.
6. The systematic error in the measurement of the Crab slope between pairs of outer pixels (for source pixels) is ± 0.10 in Γ .
7. The measured power-law indices for Crab spectra from nonsource pixels are too flat by 10%–25%. This is a $\gtrsim 10\%$ –20% effect in flux at greater than 5 keV and may also result from not accounting for the energy-dependent mirror PSF.

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