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A SEARCH FOR X-RAY POLARIZATION IN COSMIC X-RAY SOURCES

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ABSTRACT

Fifteen strong X-ray sources were observed by the X-ray polarimeters on board the *OSO 8* satellite from 1975 to 1978. The final results of this search for X-ray polarization in cosmic sources are presented in the form of upper limits for the 10 sources which have not been discussed elsewhere. These limits in all cases are consistent with a thermal origin for the X-ray emission.

Subject headings: nebulae: supernova remnants — polarization — X-rays: binaries — X-rays: sources

I. INTRODUCTION

X-ray polarization can serve as a useful probe into the mechanisms and geometries of high-energy emission from celestial objects. When the emission is nonthermal, e.g., synchrotron radiation or linear bremsstrahlung, studying the magnitude, direction, and energy dependence of the polarization can yield information about the nonisotropic electron velocity distribution and associated magnetic fields and their configurations. Even when the intrinsic emission mechanism is unpolarized, scattering can lead to polarization of the emergent radiation. In binary X-ray sources, for example, the amount and angle of polarization may constrain the geometry of the source (Angel 1969) and, for accretion disks, the inclination angle (Chandrasekhar 1960). The measurement of polarization does not uniquely determine a source model, but polarimetric results may allow one to distinguish between different models suggested by photometric, spectral, and temporal data.

Novick *et al.* (1972) were the first to detect X-ray polarization in a cosmic X-ray source, the Crab nebula; their sounding rocket observation proved that the X-ray emission in the nebula was due to synchrotron radiation. Subsequent polarimetry experiments were carried out on two satellites, *Ariel V* (Griffiths, Ricketts, and Cooke 1976; Gowen *et al.* 1977) and *OSO 8*. In this article, we summarize the results which were obtained with the Bragg crystal polarimeters on *OSO 8*. A total of 15 celestial X-ray sources were observed using this experiment; the results of the data from 10 of these objects have not been discussed previously. Polarization was not detected in any of these new sources, and therefore all of the new results are in the form of upper limits.

II. OBSERVATIONS AND DATA ANALYSIS

The polarimetry experiment on *OSO 8* consisted of two identical polarimeters; each polarimeter was made up of graphite crystals ($2d = 6.70$ Å) mounted upon a parabolic surface which focused Bragg-reflected X-rays into a gas-filled proportional counter. The axes of the diffracting panels were co-aligned with the spin axis of the satellite, which rotated about the line of sight to a given X-ray source once every 10 s. Because of the polarization dependence of Bragg reflection, the diffracted flux from a polarized source located along the spin axis was modulated at twice the rotation period of the satellite. The phase of the modulation gave the polarization angle, and the amplitude gave the fractional polarization. The mean angle of incidence for X-rays was 45°; hence first- and second-order Bragg reflections at the crystal panels occurred at 2.6 keV and 5.2 keV. The modulation factor, M (the measured response to a 100% linearly polarized beam), was 93%. The polarimeters have been described in more detail by Novick (1975).

Fifteen distinct X-ray sources were observed with the *OSO 8* polarimeters during the lifetime of the mission. Observations lasted from 2 to 11 days. Table 1 lists for each source: column (1), the *Uhuru* designation; column (2), the common name of the source; column (3), observation dates; column (4), the amount of useful data; and in column (8), the nature of the X-ray source. Columns (5), (6), and (7) contain spectral parameters and count rates to be described below. Typically the amount of useful data taking time was 15% of the length of the observation. Data were rejected during those times when the source was occulted by the Earth as well as during those portions of the orbit in which the charged particle rates were large. The remaining data were sorted into various types depending upon, for example, whether the satellite was viewing a source on axis in the sunlit sky or in the nighttime. There were also several types of background measurements: those obtained when the polarimeter field of view was occulted by the Earth; also when the spin axis was greater than 5° from the direction to the source; and in some cases when the X-ray source was in binary eclipse. Pulse height information allowed us to consider the energy bandwidths separately, as well. The data of each type at both energy bandwidths and for each polarimeter were analyzed separately, and the results for the two polarimeters and the day and night types were combined by time averaging.

The data of each type were binned into 90 azimuth bins (4° width) referenced to celestial north, and binning for valid events was determined by the orientation of the satellite at the photon time of arrival. A count rate was computed for each bin by dividing the counts per bin by the corresponding exposure time, and then this was fitted by the least squares method to the function $f(\theta)$:

$$f(\theta) = a_0 + a_1 \cos\theta + b_1 \sin\theta + a_2 \cos 2\theta + b_2 \sin 2\theta$$

TABLE 1

OSO 8 POLARIMETRY OBSERVATIONS

4U Source (1)	Common Name (2)	Observation Dates (3)	Exposure (days) (4)	Power-Law Fit: Index (5)	Power-Law Fit: Counts (6)	Range of *Uhuru* Counts (7)	Source Type (8)
4U 0316+41	Perseus cluster	1976: 047–049	0.37	Not detected		46.8–48.0	Cluster of galaxies
		1977: 045–051	1.94	−1.22	90		
4U 0531+21	Crab nebula	1976: 071–077	1.86	−2.10[a]	910	926–968	SNR pulsar
		1977: 074–079	1.11	−2.10[a]	920		
		1978: 071–076	1.19	Gain changed			
4U 1118−60	Cen X-3	1975: 199–207	1.59	−0.66	220	<20–200	Binary pulsar
		1978: 197–208	1.98	−1.20	50		
4U 1617−15	Sco X-1	1977: 238–242	1.24	−1.75	11900	6800–17000	Binary
		1978: 236–244	2.17	−1.59	12200		
4U 1636−53	...	1976: 249–254	0.52	−1.80	120	125–250	Burster
4U 1656+35	Her X-1	1975: 241–245	1.11	−0.08	310	10–100	Binary pulsar
4U 1658−48	GX 339-4	1978: 255–258	0.66	−4.06	100	120–350	Bulge source
4U 1702−36	GX 349+2	1975: 254–255	0.12	−1.32	750	375–750	Bulge source
4U 1758−25	GX 5-1	1975: 263–264	0.22	−1.25	1020	575–1150	Bulge source
4U 1820−30	...	1976: 268–273	2.10	−1.48	250	110–320	Burster in globular cluster NGC 6624
		1978: 268–274	1.57	−1.48	310		
4U 1837+04	Ser X-1	1975: 276–278	0.14	−1.68	250	140–280	Burster
4U 1956+35	Cyg X-1	1975: 311–314	0.59	−2.26	780		
		1976: 308–315	1.67	−1.45	340	235–1175	Binary
		1977: 305–314	3.34	−1.40	330		
4U 2030+40	Cyg X-3	1975: 323–329	1.32	−0.49	90	190–385	Binary
		1976: 322–327	2.03	−0.25	70		
4U 2141+38	Cyg X-2	1975: 343–345	0.98	−1.86	440		
		1976: 338–345	1.35	−1.50	370	275–550	Low-mass binary
		1977: 338–346	1.02	−1.72	580		
4U 2321+58	Cas A	1976: 021–023	0.24	−3.28	70	52.4–54.4	SNR

[a] Crab nebula used as calibration standard; this value is by definition.

with θ as the azimuth angle. The mean source count rate plus background is a_0; the coefficients a_2 and b_2 are related to the Stokes parameters Q and U (linear polarization in NS–EW and NESW–NWSE directions) by

$$Q = -a_2/M \quad \text{and} \quad U = -b_2/M \; .$$

The fractional polarization

$$P = \frac{(Q^2 + U^2)^{1/2}}{I} \; ,$$

where I is the mean source count rate, i.e., a_0 minus the instrumental background count rate, determined during the Earth-occulted portion of the orbit. The polarization angle

$$\phi = \frac{1}{2} \arctan \left(\frac{U}{Q}\right) \; ,$$

measured positive east of north.

In the absence of systematic errors, the Stokes parameters Q and U are normally distributed quantities. Polarization, however, is a positive definite number, and therefore random fluctuations in Q and U yield nonzero values for polarization even for an unmodulated source. The relevant statistic is the probability π of obtaining the measured polarization or greater by chance from an unpolarized source,

$$\pi = \exp\left[-(Q^2 + U^2)/4\sigma^2\right] \; ,$$

where σ is the error in the count rate.

Most galactic X-ray sources are highly variable. In order to estimate the approximate *Uhuru* count rate of these sources during our observations, we have adopted the following procedure. As described earlier, this experiment determines, among other quantities, a count rate at two energies with known bandwidths. These two spectral points can be used to calculate a photon index for a power-law fit. We used the Crab nebula as a calibration standard, viz., by obtaining factors to convert from the polarimeter count rate to source photon flux at both 2.6 keV and 5.2 keV. These factors were then used throughout this analysis for all the sources, ignoring differences in interstellar absorption. The Crab spectrum used was (Toor and Seward 1974)

$$\frac{dN}{dE} = 10.0 \, E^{-2.10} \; ,$$

where dN/dE is the differential photon flux. The results are also presented in Table 1; columns (5) and (6) contain the photon index and equivalent number of *Uhuru* counts for a power-law spectrum, and column (7) lists the minimum and maximum range of *Uhuru* counts obtained from the Fourth *Uhuru* Catalog (Forman *et al.* 1978).

III. RESULTS AND DISCUSSION

Table 2 presents upper limits on the polarization of 10 sources separated according to energy and year. The source designation appears in column (1) and the year of observation in column (2). Column (3) contains the source intensity at 2.6 keV after appropriate background subtraction; the 5.2 keV intensity is in column (6). The probability, π, that the measured modulation (or greater) was obtained by chance

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TABLE 2

POLARIZATION UPPER LIMITS

		ENERGY					
		2.6 keV			5.2 keV		
SOURCE (1)	YEAR (2)	I (cts per 1000 s) (3)	π (4)	Upper Limit (5)	I (cts per 1000 s) (6)	π (7)	Upper Limit (8)
4U 0316+41	1976	24.62 ± 5.13	0.58	25.4%	Not detected	...	...
	1977	21.34 ± 0.63	0.62	15.9%	7.14 ± 0.50	0.40	34.5%
	Comb	21.39 ± 0.63	0.88	12.6%	...	...	...
4U 1118−60[a]	1975	44.69 ± 0.93	0.55	14.1%	21.25 ± 0.74	0.87	19.8%
	1978	11.75 ± 1.06	0.16	71.6%	3.85 ± 0.89	0.43	100.0%
	Comb	30.36 ± 0.70	0.18	18.2%	14.14 ± 0.57	0.49	27.0%
4U 1636−53	1976	36.25 ± 1.00	0.83	15.3%	7.82 ± 0.72	0.33	60.1%
4U 1656+35[a]	1975	10.76 ± 1.26	0.96	62.1%	3.27 ± 1.13	0.20	100.0%
4U 1658−48	1978	48.19 ± 1.09	0.95	10.4%	2.17 ± 0.70	0.17	100.0%
4U 1702−36	1975	194.25 ± 3.45	0.92	9.2%	58.67 ± 2.17	0.55	22.0%
4U 1758−25[b]	1975	254.97 ± 2.96	...	...	80.99 ± 1.92	...	...
4U 1820−30	1976	66.87 ± 0.96	0.64	6.0%	18.11 ± 0.77	0.48	14.4%
	1978	85.18 ± 1.15	0.40	8.0%	23.05 ± 0.76	0.72	15.7%
	Comb	74.39 ± 0.74	0.50	4.7%	20.61 ± 0.54	0.42	10.8%
4U 1837+04	1975	73.35 ± 2.19	0.62	17.9%	17.21 ± 1.44	0.04	64.8%
4U 2321+58	1976	30.88 ± 3.24	0.66	26.4%	2.40 ± 2.42	0.26	100.0%

[a] Binary eclipse background data subtracted from I, Q, and U.
[b] Contaminated by off-axis source 4U 1744−26.

from an unpolarized source appears in column (4) for first-order results and in column (7) for second-order results. The upper limits to polarization are in columns (5) (2.6 keV) and (8) (5.2 keV) and represent the extreme values of polarization on the 99% confidence level contours.

The measurement of polarization using the *OSO 8* satellite was complicated by several systematic effects which included solar X-rays scattered from the Earth's atmosphere into the experiment, the anisotropy of charged particle instrumental background, and the presence of additional X-ray sources in the 4°.5 field of view of the polarimeter. These effects were analyzed in some detail by Long, Chanan, and Novick (1980), and we have included their estimates of the modulation expected from charged particles and scattered solar X-rays into the polarization upper limits presented here. For each observation the statistical error on Q and U was added in quadrature to a charged particle instrumental modulation of 0.28×10^{-3} s^{-1} (first order) or 0.32×10^{-3} s^{-1} (second order) and the modulation due to scattered solar X-rays of 0.62×10^{-3} s^{-1} (first order) or 0.23×10^{-3} s^{-1} (second order) to yield a total error on Q and U. This value was used in determining the 99% confidence level contours for the polarization. The presence of an off-axis source was only important during the observation of 4U 1758−25. The modulation measured during this observation was demonstrated to be a result of X-rays from source 4U 1744−26, which was 3°.4 off-axis (see Long, Chanan, and Novick 1980). Hence for this source, we have only presented the count rate.

a) *Binary X-Ray Sources*

Many of the sources observed by this instrument have long been suspected to involve thermal X-ray emission processes. It has been proposed that the bulge sources, binary sources, and X-ray bursters radiate X-rays from some type of accretion flow onto a compact object. The X-ray polarization properties expected depend on the detailed accretion scenarios, i.e., the existence of a strong dipole B-field, the presence of a disk, X-ray reflection off a companion star (Rees 1975; Lightman and Shapiro 1975). Thus, the interpretation of upper limits obtained for a specific object is quite complicated and certainly involves details of geometry and sometimes time-dependent effects. The upper limits presented here are not sensitive enough to be able to constrain detailed geometric effects (except possibly for inclination angle; see the discussion of 4U 1820−30 below) or to examine binary phase-dependent polarization. Nevertheless, the *OSO 8* observations show that the time-averaged polarization of strong compact X-ray sources is small, certainly less than 10%. At 2.6 keV, the time-averaged polarization of Sco X-1 and Cygnus X-1 is 0.39 ± 0.20% (Long *et al.* 1979) and 2.4 ± 1.1% (Long, Chanan, and Novick 1980). The restrictive upper limits on sources such as 4U 1636−53 (15.3%), GX 339−4 (10.4%), GX 349+2 (9.2%), and 4U 1820−30 (4.7%) which we present here, are consistent with a thermal origin for the emission in an electron scattering dominated region, but the detailed interpretation of the results depends upon the exact emission geometry. For example, in a geometrically thin disk with a large optical depth to electron scattering, the expected polarization varies from zero for viewing a disk face-on ($i = 0°$) to a maximum of 11.7% for an edge-on view ($i = 90°$) (Chandrasekhar 1960). For one source, 4U 1820−30, which is the brightest X-ray source associated with any globular cluster, the upper limit to the polarization at 2.6 keV implies that the inclination, assuming such an accretion disk geometry, is less than 76°.

b) *Supernova Remnants*

The Crab nebula is the brightest supernova remnant (SNR) in the sky at X-ray energies above 2 keV. The observations with the *OSO 8* polarimeters have yielded a time- and energy-averaged value for the X-ray polarization of 19.2% ± 0.9% at a position angle of 155°.8 ± 1°.4 (Weisskopf *et al.* 1978). We have also obtained the polarization of the Crab nebula at 7.8 keV (third-order Bragg reflection) from the 1978 observations. At this energy, the polarization of the nebula (including pulsar contamination) is 54.5% ± 28.4% at an angle of 137° ± 16°, consistent with the above value for the lower energy 1976 and 1977 averaged results. These values are consistent with the polarization at optical wavelengths when the optical polarization map (Oort and Walraven 1956) is integrated over the region of the nebula where X-ray emission arises. The observation of linear polarization in the nebula throughout the electromagnetic spectrum proves that synchrotron radiation is dominating the emission.

Cas A, the next brightest SNR at X-ray wavelengths, is 20 times fainter than the Crab nebula. This SNR has a radio polarization of ~4.5% aligned tangentially around the edge of the remnant (Mayer and Hollinger 1968); unlike the Crab nebula, Cas A is not currently dominated by energy supplied from a rotating neutron star. The *OSO 8* polarimeters were not sufficiently sensitive to measure Cas A's X-ray polarization, even if the fractional polarization were as great as that in the Crab nebula. Furthermore, high-resolution observations of the X-ray spectrum of Cas A show that its emission is dominated by line radiation from a shock heated plasma. Therefore, it is not surprising that polarization was not detected; in future, much more sensitive polarimetric observations are necessary to determine what portion of the emission is from the synchrotron process.

IV. CONCLUSION

We have used the polarimeters on board the *OSO 8* satellite in an attempt to determine the linear X-ray polarization of various bright galactic sources. We present here the results of the observations in the form of upper limits to the magnitude of polarization which are consistent with emission from thermal sources. To further constrain the X-ray emission from such sources, more sensitive polarimetric observations, at about the 1% level, are required. Such sensitivities are envisioned for AXAF.

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