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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 ten 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 (Chandrasekar 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 et al. 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 ten 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 ($2d = 6.70\text{\AA}$) 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 sec. 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: (1) the Uhuru designation, (2) the common name of the source, (3) observation dates, (4) the amount of useful data, and in the last 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 fit by the least squares method to the function $f(\theta)$:

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

with θ as the azimuth angle. The mean source counting 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 counting rate, i.e., a_0 minus the instrumental background counting 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 non-zero 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,

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

where σ is the error in the counting rate.

Most galactic X-ray sources are highly variable. In order to estimate the approximate Uhuru counting 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

$$\frac{dN}{dE} = 10.0 E^{-2.10} \quad (\text{Toor and Seward 1974}),$$

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 4 Uhuru catalog (Forman *et al.* 1978).

III. RESULTS AND DISCUSSION

Table 2 presents upper limits on the polarization of ten 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 observed polarization (or greater) was obtained by chance from an unpolarized source appears in column (4) for the first order results and in column (7) for second order. 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.

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 for different accretion scenarios, e.g., accreting neutron stars, accretion disks around black holes, or X-rays scattered off companion stars, have been studied by Rees (1975) and Lightman and Shapiro (1975). The application of any of these models to a specific object, however, is quite complicated and certainly involves details of geometry and sometimes time dependent effects, as in the scattering of X-rays off a companion in a binary system. 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 4U1820-30 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 $0.39 \pm 0.20\%$ (Long et al. 1979) and $2.4 \pm 1.1\%$ (Long et al. 1980). The restrictive upper limits on sources such as Cen X-3 (10.1%), 4U1636-53 (14.0%), GX 339-4 (9.4%), GX 349+2 (9.1%), and 4U1820-30 (4.0%) which we present here, are consistent with a thermal origin for the emission in an electron scattering dominated disk, as was expected considering the lack of strong narrow line emission in most of these sources. 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 ($i = 0^\circ$) to a maximum of 11.7% for an edge-on view ($i = 90^\circ$) (Chandrasekhar 1960). For one source, 4U1820-30, 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 73° .

b) Supernova Remnants

The Crab Nebula is the brightest supernova remnant (SNR) in the sky at X-ray energies above about 2 keV. The observations with the OSO-8 polarimeters have yielded a time- and energy-averaged value for the X-ray polarization of $19.2 \pm 0.9\%$ at a position angle of $155^\circ 8 \pm 1^\circ 4$ (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 $54.5\% \pm 28.4\%$ at an angle of $137^\circ \pm 16^\circ$, 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 twenty times fainter than the Crab Nebula. This SNR has a radio polarization of $\sim 4.5\%$ 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; 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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TABLE 1
OSO-8 POLARIMETRY OBSERVATIONS

4U Source (1)	Common Name (2)	Observation dates (3)	Exposure (days) (4)	Power Law fit Index (5)	Counts (6)	Range of Uhuru cts (7)	Source type (8)
4U0316+41	Perseus cluster	1976 : 047-049 1977 : 045-051	0.37 1.94	Not detected -1.22	90	46.8 - 48.0	Cluster of galaxies
4U0531+21	Crab Nebula	1976 : 071-077 1977 : 074-079 1978 : 071-076	1.86 1.11 1.19	-2.10 ^a -2.10 ^a Gain changed	910 920	926 - 968	SNR pulsar
4U1118-60	cen X-3	1975 : 199-207 1978 : 197-208	1.59 1.98	-0.66 -1.20	220 50	< 20 - 200	Binary pulsar
4U1617-15	Sco X-1	1977 : 238-242 1978 : 236-244	1.24 2.17	-1.75 -1.59	11900 12200	6800 - 17000	Binary
4U1636-53		1976 : 249-254	0.52	-1.80	120	125 - 250	Burster
4U1656+35	Her X-1	1975 : 241-245	1.11	-0.08	310	10 - 100	Binary pulsar
4U1658-48	GX 339-4	1978 : 255-258	0.66	-4.06	100	120 - 350	Bulge source
4U1702-36	GX 349+2	1975 : 254-255	0.12	-1.32	750	375 - 750	Bulge source
4U1758-25	GX 5-1	1975 : 263-264	0.22	-1.25	1020	575 - 1150	Bulge source
4U1820-30		1976 : 268-273 1978 : 268-274	2.10 1.57	-1.48 -1.48	250 310	110 - 320	Burster in globular cluster NGC 6624
4U1837+04	Ser X-1	1975 : 276-278	0.14	-1.68	250	140 - 280	Burster
4U1956+35	Cyg X-1	1975 : 311-314 1976 : 308-315 1977 : 305-314	0.59 1.67 3.34	-2.26 -1.45 -1.40	780 340 330	235 - 1175	Binary
4U2030+40	Cyg X-3	1975 : 323-329 1976 : 322-327	1.32 2.03	-0.49 -0.25	90 70	190 - 385	Binary
4U2141+38	Cyg X-2	1975 : 343-345 1976 : 338-345 1977 : 338-346	0.98 1.35 1.02	-1.86 -1.50 -1.72	440 370 580	275 - 550	Low mass binary
4U2321+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

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TABLE 2

POLARIZATION UPPER LIMITS

Source	Year	Energy					
		2.6 keV			5.2 keV		
		I (Cts/1000sec)	π	Upper Limit	I (Cts/1000sec)	π	Upper Limit
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
4U0316+41	1976	24.62 \pm 5.13	0.58	23.5%	Not detected		
	1977	21.34 \pm 0.63	0.62	11.6%	7.14 \pm 0.50	0.40	29.4%
	Comb	21.39 \pm 0.63	0.88	9.4%			
4U1118-60	1975 ^a	44.69 \pm 0.93	0.55	13.1%	21.25 \pm 0.74	0.87	18.9%
	1978 ^b	11.75 \pm 1.06	0.01	31.5%	3.85 \pm 0.89	0.56	54.6%
	Comb	30.36 \pm 0.70	0.06	10.1%	14.14 \pm 0.57	0.74	12.4%
4U1636-53	1976	36.25 \pm 1.00	0.83	14.0%	7.82 \pm 0.72	0.33	54.0%
4U1656+35	1975 ^a	10.76 \pm 1.26	0.96	58.7%	3.27 \pm 1.13	0.20	100.0%
4U1658-48	1978	48.19 \pm 1.09	0.95	9.4%	2.17 \pm 0.70	0.17	100.0%
4U1702-36	1975	194.25 \pm 3.45	0.92	9.1%	58.67 \pm 2.17	0.55	21.9%
4U1758-25	1975	254.97 \pm 2.96	0.01	10.0%	80.99 \pm 1.92	0.40	13.9%
4U1820-30	1976	66.87 \pm 0.96	0.64	4.9%	18.11 \pm 0.77	0.48	12.1%
	1978	85.18 \pm 1.15	0.40	7.5%	23.05 \pm 0.76	0.72	14.6%
	Comb	74.39 \pm 0.74	0.50	4.0%	20.61 \pm 0.54	0.42	9.5%
4U1837+04	1975	73.35 \pm 2.19	0.62	17.6%	17.21 \pm 1.44	0.04	64.2%
4U2321+58	1976	30.88 \pm 3.24	0.66	25.3%	2.40 \pm 2.42	0.26	100.0%

^a Binary eclipse background data subtracted from I, Q, and U.^b Binary eclipse background rate subtracted from I.

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