SEARCH FOR X-RAY POLARIZATION IN Sco X-1*

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An x-ray polarimeter sensitive to x rays in the energy range from 6 to 18 keV, flown above the atmosphere on 27 July 1968, was used both to set an upper limit on the polarization of Sco X-1 and to check for spurious indications of polarization which might result from the anisotropy of the cosmic rays. Within the statistical limitations of the data, no evidence was found for spurious background polarization.

A Thomson-scattering x-ray polarimeter sensitive in the spectral range of about 6 to 18 keV was flown from the White Sands Missle Range at 0356 UT on 27 July 1968 in an Aerobee-150 sounding rocket. Initially the instrument was pointed at Sco X-1; later it was pointed to a region free from known point x-ray sources to check for apparent polarization that might arise from the anisotropy of primary cosmic-ray protons and terrestrial-albedo gamma rays. Within the statistical limitations of the experiment, we found no evidence either for polarization of the x rays from Sco X-1 or for spurious instrumental polarization from the cosmic-ray background. The polarimeter provides a direct measure of the normalized Stokes parameters and the components of the polarization vector $Q/I=p_x=p\cos2\theta$ and $U/I=p_y=p\sin2\theta$, where p is the magnitude of the polarization and θ is the position angle. For Sco X-1 we obtain $Q/I=p_x=(-4.9\pm6.0)\%$ and $U/I=p_y=(5.4\pm6.0)\%$. The 6.0% uncertainty given for each of these quantities includes the uncertainties in both the background and source measurements.

The interest in stellar x-ray polarization is stimulated by the hope of obtaining information about source mechanisms. Polarization could be expected if the emission process were synchrotron radiation.[1] The fact that Sco X-1 shows spectral characteristics similar to those of an old nova,[2] the absence of appreciable polarization in the visible region of the spectrum,[3] and the exponential form of the x-ray spectrum are generally taken as evidence that the x rays are produced by thermal bremsstrahlung and not by synchrotron emission.[4] It has recently been shown that even with a thermal-bremsstrahlung model we might expect polarization of a few percent if the source is not spherically symmetric and if the electron density is great enough to give a high probability for electron scattering.[5] Finally, it is important to note that both optical and x-ray flares have been observed in Sco X-1 and that these might be polarized.[4,6-8] Clearly, a study of both the spectral and temporal dependence of polarization in Sco X-1 and in other stellar x-ray sources will be essential to a full elucidation of their structure.

The instrument used in the present work exploits the polarization dependence of Thomson scattering. The probability of scattering at an angle ψ to the electric vector of the incident radiation is proportional to $\sin^2\psi$. Metallic-lithium scattering blocks are used, with 3-atm xenon-methane proportional counters arranged to detect the radiation scattered out through the sides of the blocks. This is shown schematically in Fig. 1(a); the mounting of the polarimeter in the rocket is shown in Fig. 1(b). In use, the polarimeter is pointed toward the source and rotated about the line of sight. If the incident radiation is polarized, the counting rate in each of the counters will be modulated at a frequency equal to twice the rotation frequency of the polarimeter; the depth and phase of the modulation provide a direct measure of the magnitude and position angle of the polarization vector [see Fig. 2(a)]. This mode of operation avoids false indications of polarization that would otherwise arise from

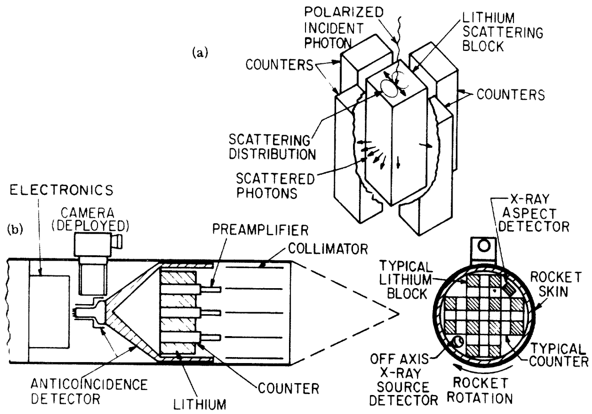

Fig. 1. (a) Schematic representation of the polarimeter concept. (b) Mounting of the polarimeter and ancillary equipment in the rocket.

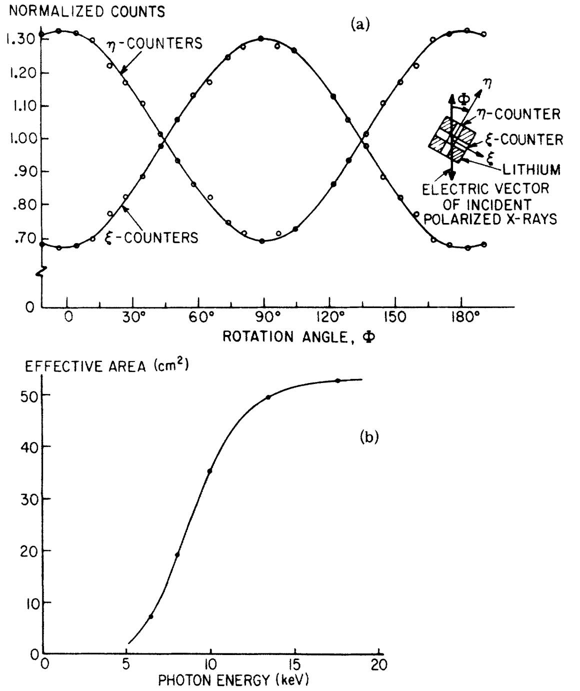

Fig. 2. (a) Variation in the counting rates for each of the orthogonal counters as the polarimeter is rotated with respect to a beam of 100%-polarized x rays. The counting rates have been normalized to their average values. (b) Variation in the effective area of the polarimeter with photon energy. Note that the geometrical area of the polarimeter is about 900 cm^2.

differences in the counter sensitivities, amplifier gains, and pulse-height discriminator levels. Clearly, the modulation components of the orthogonal counters must be in antiphase; this fact allows us to discriminate against rapid changes in source strength which might otherwise appear as polarization. The size of the blocks is determined by the mean scattering length in lithium, about 10 cm. The blocks are 12.7 cm deep, sufficient to give a 70% probability of scattering, while the cross section of 25 cm^2 is small enough to avoid multiple scattering. The measured effective area of the polarimeter for unpolarized x rays is shown in Fig. 2(b). The limits of sensitivity of the polarimeter are determined at low energies by the photoelectric absorption in the lithium and at high energies by the transparency of the counter gas to hard x rays.[9]

The response of a single polarimeter module[10] to a beam of 100%-polarized bremsstrahlung x rays with average energy of 15 keV is shown in Fig. 2(a). Here are shown the counting rates in each of the sets of orthogonal counters as a function of the orientation. These rates have been normalized to their average values. As expected, the counts in the two sets of orthogonal counters vary harmonically with angle according to the equations

$$N_\xi = R_0(1 - M_0 \cos 2\Phi),$$

$$N_\eta = R_0(1 + M_0 \cos 2\Phi).$$

Here R_0 is the average counting rate, and M_0 is the depth of modulation for 100%-polarized x rays; the axes ξ and η and the rotation angle Φ are defined in Fig. 2(b). Because each of the detectors subtends a large solid angle, the modulation depth M_0 has a value of only 31.6% for a 100%-polarized beam. Any attempt to increase the depth of modulation by decreasing the solid angle of the counters would reduce the efficiency and increase the minimum detectable polarization.

There are additional possible sources of systematic errors that must be considered. If the instrument were not pointed directly at the x-ray source, orthogonal detectors would not be equally illuminated, and a false indication of polarization would be obtained. Laboratory experiments showed that the instrument axis had to be pointed within 3° of the source to keep this effect small. To check the proper orientation of the rocket, a movie camera to photograph the star field and a collimated forward-looking x-ray detector were built into the instrument. Spurious polarization could also be caused by a nearby weak x-ray source close enough to fall within the field of view of the polarimeter. To check for such sources near Sco X-1 that might not have been discovered by other surveys, a detector was incorporated with a field of view extending from 3° to about 12° from the axis of the polarimeter. A third systematic error could be contributed by the background counts arising from cosmic rays and albedo gamma rays from the earth's atmosphere. Anisotropy of this radiation could result in orientation dependence of the background counting rate. A measurement of the background counting rate was carried out on a prototype instrument flown to a height of 95 000 ft in a balloon. The instrument was rotated about a vertical axis, and a search was made for apparent polarization effects that might arise from the known east-west anisotropy of the cosmic-ray protons. No effect large enough to affect the present results was observed.

The payload is illustrated in Fig. 1(b). After the cone is ejected, x rays enter the scattering blocks through a collimator which gives a clear view up to 3° from the axis and is totally opaque for angles greater than about 12°. This collimator prevents illumination by other x-ray sources and severely limits the signal from the isotropic background. The counter-scatterer assembly is surrounded by an anticoincidence shield of scintillating plastic viewed by a 3-in. photomultiplier tube. The movie camera, which runs at four frames a second, is deployed from the side of the rocket and records the star field down to fourth magnitude. The two forward-looking x-ray detectors are located in corners of the main polarimeter. Charge-sensitive preamplifiers are mounted on each counter forming the lower part of the main collimator. In the main electronic processing unit, the heights of the pulses from each amplifier which are not vetoed by the plastic scintillator are analyzed separately into four bins, corresponding to detected photon energies of 4.2-8.4 keV, 8.4-12.6 keV, 12.6-16.8 keV, and above 16.8 keV. Four scalers for each channel accumulate the counts in each energy bin and are sampled every 12 msec by the telemetry system. A detailed description of the instrument will be given elsewhere.

The flight took place at 2056 MST when the sun was below the horizon as seen from peak altitude and Sco X-1 was about 50° from the zenith. The maneuver to orient the rocket axis toward Sco X-1 was completed by 110 sec after launch, and a slow roll at 6°/sec was started. 250 sec after launch the rocket axis was moved 20° away from Sco X-1 to a blank region of the sky, where no known x-ray sources were in the field of view. A rolling motion about this axis at the same rate was continued until the payload re-entered the atmosphere at 310 sec after launch. The purpose of this second part of the experiment was to check for background modulation under the same conditions as the source observation. Both aspect systems functioned properly and showed that the rocket axis was about $2\frac{1}{4}°$ from Sco X-1.[11] This error is not large enough to cause a significant spurious effect. In addition, no weak sources were detected in the area surveyed near Sco X-1. For the first half of the observation of Sco X-1, there was intermittent corona breakdown. This trouble stopped 180 sec after launch. The early part of the data was not used in the analysis. Spectral data on Sco X-1 were obtained and will be reported elsewhere. Simultaneous with the flight, optical observations were made on Sco X-1 from both the McDonald and Cerro Tololo Observatories. Neither the optical nor the x-ray data showed any evidence of flare activity during the flight.

The two records obtained from observation of the source and the background point were analyzed for modulation at twice the rotation frequency ω by finding the best fit values of R_0, M_1, and M_2 in the equation

$$R(t)=R_0[1+M_1\sin 2\omega(t-t_0)+M_2\cos 2\omega(t-t_0)], \tag{2}$$

where $R(t)$ is the measured counting rate and t_0 is the time at which the window plane of a counter is parallel to the north-south axis. It can readily be shown that the standard deviation $\delta(M)$ in the modulation amplitudes is given by

$$\delta(M)=(2/N)^{1/2}, \tag{3}$$

where N is the total number of counts in the observation. In the case of Sco X-1, we obtained a total of 10^4 counts and, therefore, when we take into account the limited depth of modulation for 100%-polarized radiation, we find that the statistical limit on each component of the polarization vector is about 4%. This is increased to about 6% when we make the necessary background corrections. The values of R_0, M_1, and M_2 for both observations are presented in Table I. From an examination of the modulation components M_1 and M_2 and their errors $\delta(M)$, it is apparent that there is no convincing indication of modulation during either of the two observations. In the background observation, the mean modulations of the three lower bins are $M_1(B)=-0.01\%$ and $M_2(B)=-0.73\%$, with standard deviation $\delta(B)=1.71\%$. The average modulation of the signal from Sco X-1 in each energy bin is obtained by subtracting the background modulation from the modulation during the observation of Sco X-1. Combining the results from the three energy bins, we obtain the weighted averages of the modulation components: $M_1(S)=+1.70\%$, $M_2(S)=-1.55\%$, and $\delta(S)=1.87\%$. The polarization of the source is related to the modulation by M_0, the modulation depth for 100%-polarized radiation. We obtain, finally, for the Stokes parameters and the components of polarization of Sco X-1

$$Q/I=p_x=-4.9\%,\quad U/I=p_y=+5.4\%,\quad \delta(P)=6.0\%, \tag{4}$$

where $\delta(P)$ is the standard deviation of these quantities and includes the statistical uncertainty

Table I. Results of fitting data by Eq. (2). Here $\sigma(M)$ is the standard deviation of the components of modulation M_1 and M_2; N is the number of counts during the observation.

Energy bin	Detected photon energy range (keV)	R_0	M_1 (%)	M_2 (%)	$\sigma(M)$	N
			On Sco X-1			
1	4.2- 8.4	8.26	−0.3	+2.3	1.5	8416
2	8.4-12.6	9.15	+2.2	−2.5	1.5	9331
3	12.6-16.8	5.87	+3.0	+3.4	1.8	5994
4	Above 16.8	21.85	−1.4	−0.4	0.9	22296
			Off Sco X-1			
1	4.2- 8.4	3.47	−0.1	−0.2	2.8	2491
2	8.4-12.6	2.74	−0.5	+1.3	3.2	1974
3	12.6-16.8	3.23	0	−3.1	2.9	2334
4	Above 16.8	21.22	−0.2	−1.4	1.1	15331

in both the background and source measurements. This corresponds to a polarization of magnitude 6.90% at position angle 63°. The result is consistent with an unpolarized source in that the average magnitude of repeated measurements of the same precision on an unpolarized source is expected to be 7.4%. This finite result arises from the fact that polarization is a positive definite quantity obtained from the quadratic sum of components, each of which has a null expectation value if the source is unpolarized but is a stochastic quantity. An analysis shows that the probability of obtaining the present 6.9% or larger result from a single measurement of an unpolarized source is 51%, while if the source polarization were 20%, the probability of obtaining 6.9% or less is only 0.7%.

To summarize, we have shown that the lithium-scattering polarimeter is free from significant systematic errors and have used it to set an upper limit on the polarization from Sco X-1. The absence of polarization within our limits of error is not unexpected and lends weight to the belief that the x-ray emission is thermal bremsstrahlung.

We would like to thank Professor L. Woltjer for his invaluable guidance, support, and encouragement. Much of the initial work on the polarimeter and many of the techniques of construction were developed by Dr. T. Wing and Dr. F. Kantor. The computer analysis of the flight telemetry data was developed by Mr. R. Linke. This work would not have been possible without the enthusiastic support of the entire staff of the Columbia Laboratory, especially that of Mr. C. Dechert, Miss J. Ladue, and Mr. S. Fisher. We are indebted to Mr. W. Sippach, Mr. H. Cunitz, and Mr. E. Taylor of the Nevis Laboratories for the design and construction of the electronics. We are grateful to Dr. R. Jastrow, Dr. G. Pieper, and N. Roman for their support, and to the National Aeronautics and Space Administration and the U. S. Navy rocket crews for the preparation and successful launching of the rocket.

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[9] The data shown in Fig. 2(b) do not extend to an energy high enough to show the decrease in efficiency expected from the decrease in absorption in the counter gas.

[10] For ease of construction and maintenance the polarimeter is built in modular form. Each module consists of four counters arranged in a cross and four lithium blocks that fill in the corners of the cross.

[11] The camera data show that the axis of the polarimeter stayed within a circle of 30′ radius centered at R.A. $16^{\mathrm{h}}8^{\mathrm{m}}$, Dec −16°5′ during the Sco X-1 observations. This is 2°15′ from Sco X-1. The background observations were centered at R.A. $15^{\mathrm{h}}15.25^{\mathrm{m}}$, Dec −0°55′.

ERRATA

MUTUAL FRICTION IN He II NEAR THE SUPERFLUID TRANSITION. G. Ahlers [Phys. Rev. Letters 22, 54 (1969)].

The third line below Eq. (1) should read, "(q is in W cm^{-2})...."

MEASUREMENT OF THE K_1^0 CHARGED-TO-NEUTRAL DECAY BRANCHING RATIO. B. Gobbi, D. Green, W. Hakel, R. Moffett, and J. Rosen [Phys. Rev. Letters 22, 682 (1969)], and STUDY OF $K_1^0 \to \pi^0\pi^0$ AND $K_2^0 \to \pi^0\pi^0$ INTERFERENCE. B. Gobbi, D. Green, W. Hakel, R. Moffett, J. Rosen, B. Goz, and D. Tycko [Phys. Rev. Letters 22, 685 (1969)].

The figures for these two Letters were transposed: Those appearing with the first Letter pertained to the second, and vice versa. The captions are with the proper Letters and thus not with the figures they describe.