LINEAR POLARIZATION OBSERVATIONS OF SOME X-RAY SOURCES

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Abstract. Multicolour linear polarization of optical radiation of the X-ray sources Sco X-1, Cyg X-2, Cyg X-1 and Her X-1 was measured at the Crimean Astrophysical Observatory in 1970–1973. These observations indicate that polarization of Sco X-1 in the ultraviolet, blue and red spectral regions appears to be variable. No statistically significant variations of polarization were found for the other three sources observed.

1. Introduction

A polarimetric study of X-ray sources in the optical region was carried out as a part of their comprehensive investigation. No appreciable time-variation of the linear polarization of Sco X-1 was detected by Hiltner *et al.* (1967), Elvius (1968), Landstreet and Angel (1972) and Kemp *et al.* (1972). A conclusion about its interstellar origin was made. A wavelength dependence of polarization for Cyg X-1 was found by Gehrels and Serkowski (Gehrels, 1972). Its variability, however, was not examined. The linear polarization of Cyg X-2 was measured by Visvanathan (1967) in white light only. The wavelength dependence of polarization and its time-variations have not been studied. Visvanathan's supposition that the polarization of the object may be of interstellar origin based on the comparison of the Cyg X-2 polarization with polarization of three stars in the vicinity seems unconvincing.

In this note we present our linear polarization observations of the objects mentioned and those of X-ray source Her X-1 recently identified. The purpose of our work was to study the dependence of the polarization of the objects on wavelength and time.

2. Observations

The observations were carried out with a single-channel photoelectric polarimeter described by Shakhovskoy and Efimov (1972) at the 2.6-m telescope of the Crimean Astrophysical Observatory in 1970–1973. Most of observations discussed below were made at the Nasmyth focus. A high speed rotation (33 revolutions per second) of the analyser was used. A photon-counting technique was employed operating in the synchronous pulse accumulation regime. A multialkali photomultiplier of FEU-79 type was used as a light detector. The measurements were made in five different wavelength bands using glass colour filters with effective wavelengths 3630, 4340, 5450, 6190 and 7440 Å (*U*, *B*, *V*, *O*, *R*). A single complete observation consists of 4–16 twenty or fifty-second measurements. All observations were corrected for instrumental polarization. The residual error is about 0.1%. In most cases, intrinsic star polarization and its variations are comparable to the observational errors. Therefore, the

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reliability of the error estimation is of crucial importance in the interpretation of the results. The data were analysed by comparing standard deviations σ_q and σ_u of the normalized (to the total intensity I) mean Stokes parameters, $q=Q/I=p\cos 2\theta$ and $u=U/I=p\sin 2\theta$, to the standard deviations σ_{op} predicted from the counting statistics. The comparison shows (Figure 1) that internal errors of the observations are mainly due to the counting statistics. Due to the uncertainty in the correction for the instru-

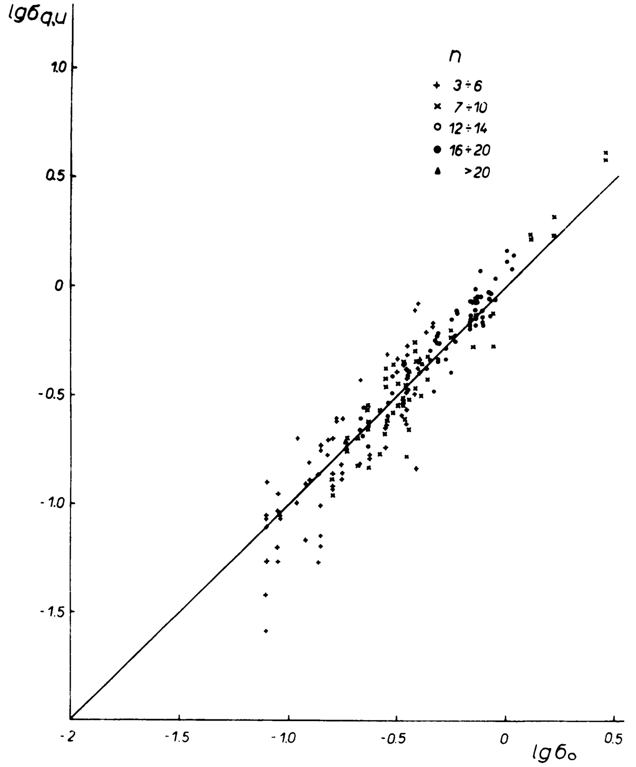

Fig. 1. The errors σ_q and σ_u for the normalized Stokes parameters from scattering in a set of measurements compared with predicted errors σ_{0p} from counting statistics. The solid line corresponds to equality of the errors.

mental polarization, external errors may be estimated from scatter in the standard stars' polarization on different nights. These values are usually much less than internal errors which make the major contribution to the complete error. The good agreement of the internal errors obtained in different ways indicates that there were no significant variations of the linear polarization within a time-scale of 10–20 min (the duration of a complete observation) at the time of observation for any object observed. In the next section results of the search for changes in polarization within a time-scale of tens of minutes or more are given.

3. Results of Observations

The main results of our observations are listed in Table I which contains: the colour, the number N of nights on which our observation were made, the number n of individual measurements, the mean polarization $\bar{p}$ and standard deviation $\sigma_{\bar{p}}$ (percent), the mean positional angle θ and standard deviation $\sigma_{\bar{\theta}}$ (degree), the mean standard

TABLE I

The mean values of polarization and standard deviations for some X-ray sources

Colour	N	n	$\bar{p}$	$\sigma_{\bar{p}}$	$\bar{\theta}$	$\sigma_{\bar{\theta}}$	$\bar{\sigma}_q$	$\bar{\sigma}_u$	$\bar{\sigma}_{0p}$	$\bar{\sigma}_{1q}$	$\bar{\sigma}_{1u}$
					Sco X-1						
U	5	71	0.64	0.36	128	16	0.81	0.82	0.50	*0.64*	*0.65*
B	10	190	0.34	0.08	127	7	0.18	0.32	0.23	–	*.22*
V	9	66	0.53	0.08	126	4	0.22	0.28	0.26	–	(0.15)
O	4	36	0.47	0.17	134	10	0.45	0.13	0.42	(0.16)	–
R	8	69	0.28	0.19	148	20	0.58	0.52	0.38	*0.44*	0.36
					Cyg X-2						
B	6	88	0.85	0.46	8	15	1.31	0.89	1.16	(0.61)	–
V	6	74	0.24	0.43	50	51	1.19	0.88	0.82	0.85	(0.32)
O	2	32	0.49	0.91	142	53	0.65	1.73	1.00	–	1.41
R	5	71	0.69	0.65	118	27	1.08	1.76	1.40	–	1.06
					Cyg X-1						
U	3	16	4.10	0.13	138.5	0.9	0.21	0.26	0.18	(0.10)	(0.18)
B	3	32	4.63	0.04	138.4	0.2	0.07	0.06	0.06	(0.04)	(0.03)
V	3	11	4.78	0.09	138.3	0.6	0.16	0.17	0.13	(0.09)	(0.10)
O	3	14	4.78	0.07	137.7	0.4	0.14	0.10	0.12	(0.08)	–
R	3	14	3.64	0.09	135.8	0.7	0.17	0.13	0.13	(0.10)	–

deviations $\bar{\sigma}_q$ and $\bar{\sigma}_u$ for one set of measurements obtained from deviations of individual sets from their overall mean; the predicted standard deviation from counting statistics $\bar{\sigma}_{0p}$ for one set, and the residual standard deviations $\sigma_{1q}=(\bar{\sigma}_q^2-\bar{\sigma}_{0p}^2)^{1/2}$ and $\sigma_{1u}=(\bar{\sigma}_q^2-\bar{\sigma}_{0p}^2)^{1/2}$ corresponding to the extra dispersion of q and u observed. Parentheses are used if the probability of the reality of a difference between $\bar{\sigma}_q$, $\bar{\sigma}_u$ and $\bar{\sigma}_{0p}$ is less than 80% and italicized if the probability of the difference is more than 95%. In the next section we discuss the results for each object.

4. Discussion

4.1. Sco X-1 = V 818 Sco

To search for possible rapid fluctuations and day-to-day variations in the polarization, we have made special observations on four nights in May – June, 1972. The observations consisted of several consecutive sets of measurements of the object in blue light. The total duration of the observations was about 1.5 – 2 h. The results are shown in Figure 2. Systematic changes in the polarization parameters exceeding the observational errors sometimes appeared. An analysis of variance shows, however, that variations of polarization on any night are not statistically significant at the 5% confidence level. We conclude that there was no evidence for variable polarization of Sco X-1 with an amplitude of more than 0.2–0.4% at the time of observation. Using statistical criteria for all these observations which form a rather homogenous sample, the real day-to-day variations of u were derived. The distribution of q (122 estimates in all) was found to differ significantly from the normal using a χ^2 test, while the similar

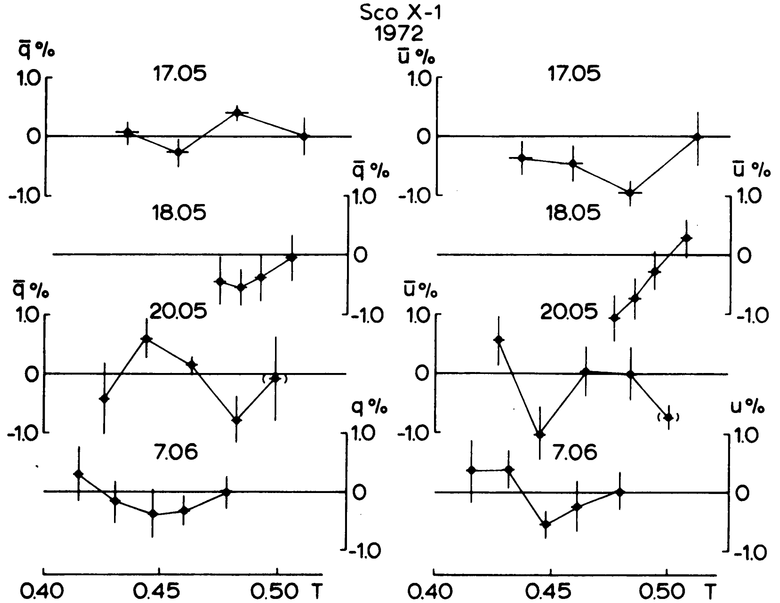

Fig. 2. Variations of normalized Stokes parameters $\bar{q}$ and $\bar{u}$ (per cent) on different nights for Sco X-1. Vertical bars correspond to the doubled standard deviation, horizontal bars represent the time interval. Abscissae are marked in time in fractions of a Julian day. Less certain observations are shown in parentheses.

distribution of u was rather close to the normal. A comparison of the multicolour observations of Sco X-1 on different nights shows a large scatter which is mainly due to the internal errors. An analysis of variance of the observations in each colour was performed to evaluate the statistical reliability of these differences. No real variations of q and/or u in V and O colours were found (see $\bar{\sigma}_q$, $\bar{\sigma}_u$ and $\bar{\sigma}_{0p}$ in Table I). However, the scattering of both Stokes parameters in U and one of them in R are significantly more at the 95% probability level than that expected from the internal errors. Thus, it is reasonable to suppose the existence of a small intrinsic polarization pronounced in R and (with less certainty) in the short-wave region. Corresponding values of $\bar{\sigma}_{1q}$ and $\bar{\sigma}_{1u}$ are given in Table I. The polarization parameters averaged in each colour are given in Table I and plotted in Figure 4 along with the data from Landstreet and Angel (1972). The solid curve is the relation

$$p/p_{\max} = \exp\left[-K\ln^2(\lambda_{\max}/\lambda)\right], \tag{1}$$

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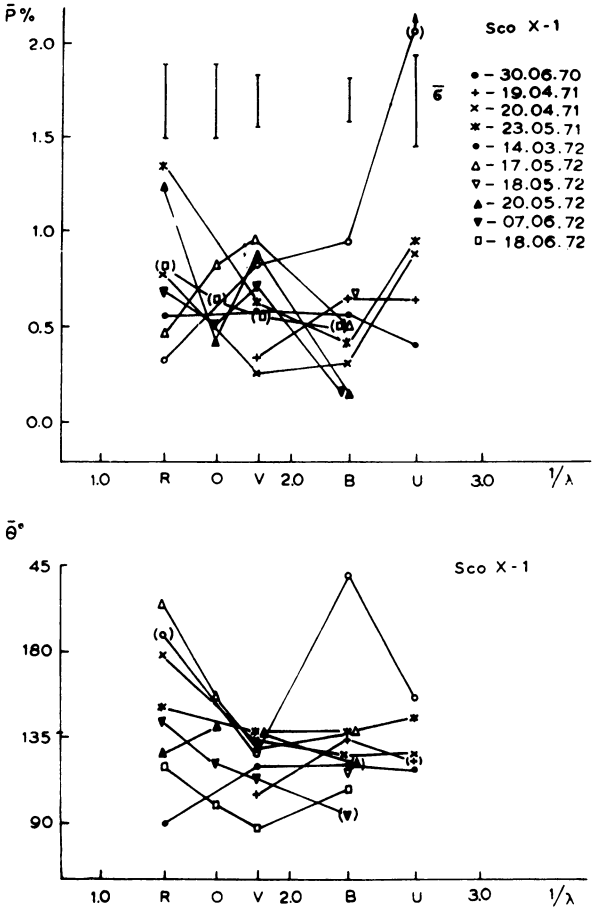

Fig. 3. The dependences of the mean degree of polarization $\bar{p}$ (per cent) and positional angle $\bar{\theta}$ (degree) on the inverse wavelength (μm^{-1}) for Sco X-1, from observations on different nights. Vertical bars at the top of the figure correspond to the mean standard error in each colour. Uncertain observations are shown in parentheses.

where $K = 1.15$, and λ is the effective wavelength for the spectral region used (Coyne *et al.*, 1974) calculated with our data. The obtained quantities $p_{max} = 0.45\%$, $\lambda_{max} = 6200$ Å and $\bar{\theta} = 128°$ are in good agreement with information on the interstellar polarization in this region of the sky.

Hence, we conclude that, in addition to interstellar polarization, a small variable intrinsic linear polarization, pronounced in red, blue and ultraviolet light exists in the Sco X-1 optical radiation. An indirect argument in support of this supposition is a discrepancy in the data on Sco X-1 circular polarization.

4.2. Cyg X-2 = V 1341 Cyg

The results of our observations are shown in Figure 5. The scattering is fairly large

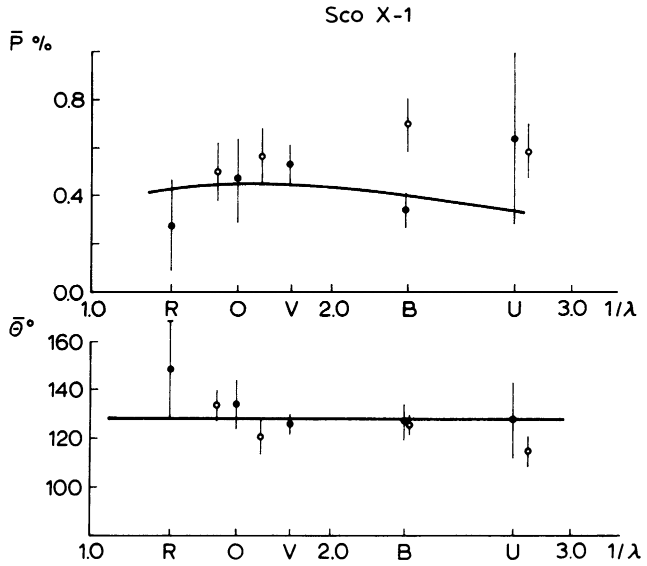

Fig. 4. The mean wavelength dependences of $\bar{p}$ and $\bar{\theta}$ for Sco X-1 from our observations (filled circles) and from Landstreet and Angel (1972) (open circles). Vertical bars correspond to the doubled standard error. The solid line is the wavelength dependence of interstellar polarization.

as is natural for such a faint object. Averaged polarization parameters for the different colours obtained from the observations in 1970–1972 are given in Table I. It seems that the Cyg X-2 linear polarization is small and cannot be interpreted unambiguously on the basis of the data available. The interstellar polarization in this region of the sky is also small. No evidence for any real variation in polarization in any colour was found from the analysis of variance at the 5% or better confidence level.

4.3. Cyg X-1 = V 1357 Cyg

To study the linear polarization of this source for short-time variability, six sets of measurements were made on one night (1971, October 15) in blue light. The time interval covered was about 3.5 h. No statistically significant differences between both individual and sets of measurements were found by the analysis of variance. Similar procedures employed for all our observations in each colour did not reveal any time variations of Stokes parameters to be real at the 5% confidence level. Averaged parameters are given in Table I. Normalized polarization-wavelength dependence calculated from our observations and that from Gehrels and Serkowski (Gehrels, 1972) is shown in Figure 6. The normalized dependence for the interstellar polarization (I) from Coyne *et al.* (preprint) is also shown. For comparison, our results for the standard star HD 183 143 are plotted in the same figure. This star is a very reddened one. Its polarization is supposed to be of purely interstellar origin.

It seems from Figure 6, that the polarization of Cyg X-1 is in a good agreement with the interstellar polarization. The deviations from the curve in colour $O(\lambda_{max}/\lambda = 0.79)$

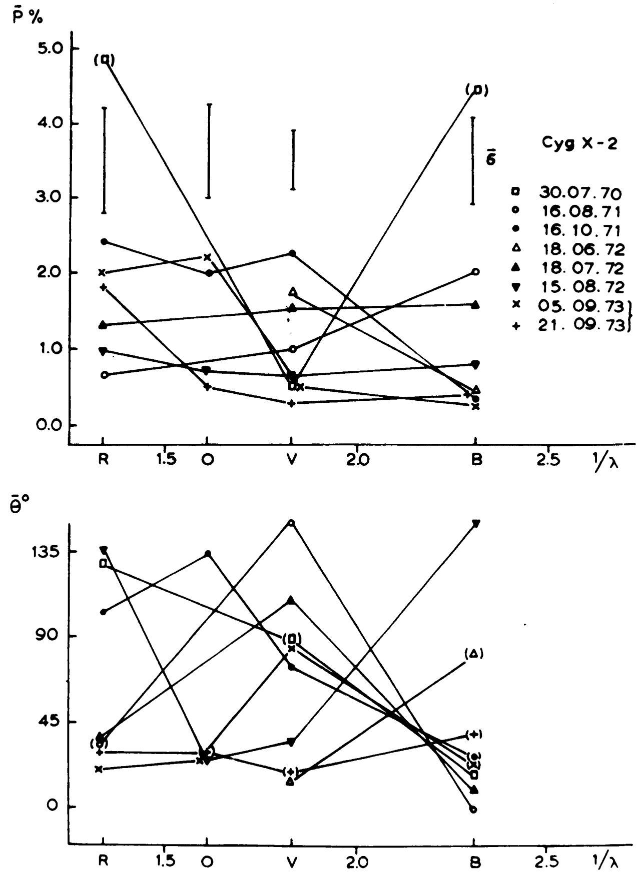

Fig. 5. The dependences of $\bar{p}$ and $\bar{\theta}$ on inverse wavelength for Cyg X-2 from our observations on different nights. The vertical bars correspond to the mean standard error in each colour. Less certain observations are shown in parentheses. The data for 1973 are preliminary.

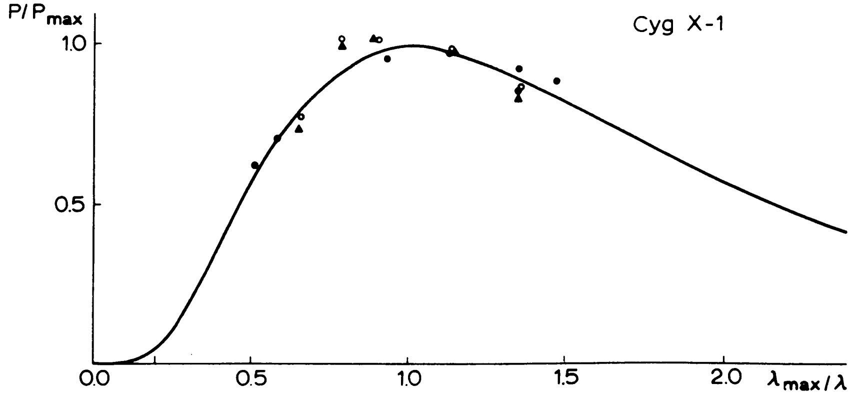

Fig. 6. The normalized polarization dependence on wavelength for Cyg X-1 from our observations (open circles) and from Gehrels and Serkowski (Gehrels, 1972) (filled circles). Triangles are the similar dependence for the standard star HD 183143 from our observations. The solid curve is the normalized wavelength dependence of interstellar polarization from Coyne *et al.* (1974).

for Cyg X-1 and HD 183 143 are apparently caused by a deficiency of our calibration in this colour for stars with a large reddening.

Therefore, the lack of linear polarization variations and the polarization dependence on the wavelength indicates beyond doubt that the polarization of Cyg X-1 is interstellar.

4.4. Her X-1 = HZ Her

A few observations indicate that the polarization of Her X-1 is apparently less than 1–1.5%. Insufficient data are available at present, however, to study the phase dependence of polarization. Further observations are needed to construct the mean polarization-wavelength dependence and to check its possible time-variation (Figure 7).

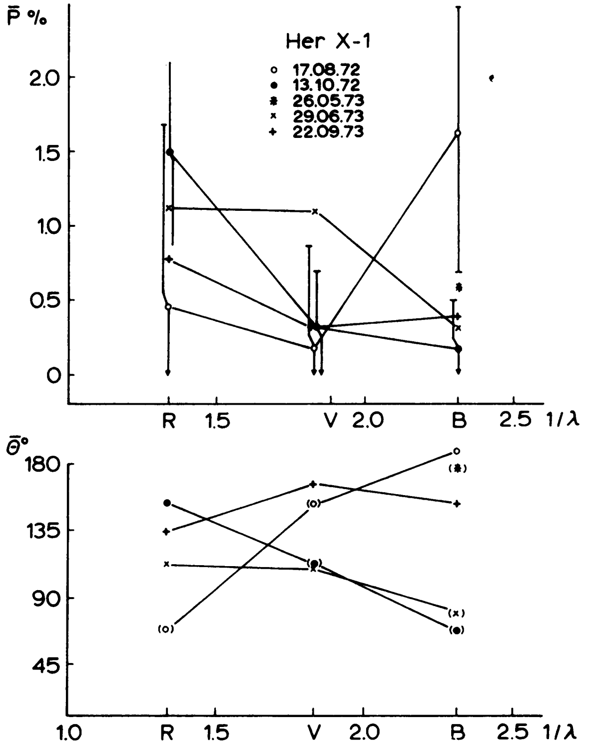

Fig. 7. The dependence of $\bar{p}$ and $\bar{\theta}$ on the inverse wavelength for Her X-1 from our observations on different nights. The vertical bars correspond to the standard error $\sigma_{\bar{p}}$. Less certain observations are shown in parentheses. The data for 1973 are preliminary.

5. Conclusions

We conclude that:

(1) The intrinsic linear polarization of galactic X-ray sources is usually less than 0.5%. Extensive observations with large telescopes are required to study it in more detail.

(2) The polarization of the objects observed is mainly interstellar.

(3) The variable intrinsic polarization of small amplitude seems to exist in the red, blue and ultraviolet spectral regions of the Sco X-1 radiation.

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