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A MEASUREMENT OF THE OPTICAL AND X-RAY EMISSION FROM SCORPIUS X-1 AND THE X-RAY DIFFUSE BACKGROUND*†

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ABSTRACT

Another simultaneous measurement of the optical and X-ray emission from Sco X-1 has been made. A rocket-borne scintillation counter was used to measure the X-ray spectrum from 4 to 40 keV. The optical intensity at the time of the X-ray measurements was $B = 12.97$ mag. The X-ray spectrum looks like thin-source thermal bremsstrahlung with an apparent plasma temperature of 7 ± 1 keV. These data are compared with previous measurements of X-ray and optical emission. It is possible that total energy emission from Sco X-1 follows the B-magnitude in a nearly linear fashion.

The diffuse X-ray background was measured in the energy range 4–70 keV. A shutter arrangement made it possible to correct accurately for the cosmic-ray contribution to the background. This measurement agrees with the previously reported spectrum.

I. INTRODUCTION

The intriguing question as to whether there is a correlation between the optical and X-ray emission from Sco X-1 has caused us to perform another simultaneous observation in the optical and X-ray regions. This experiment, conducted 1968 August 22, constituted the sixth Lawrence Radiation Laboratory experiment on the correlation between X-ray and optical emission from Sco X-1. The results of the previous experiments have been published (Chodil *et al.* 1968; Mark *et al.* 1969; Grader *et al.* 1970). This paper compares the new data with results of the previous experiments. Within the usual uncertainties, the X-ray emission from Sco X-1 again looks like thermal bremsstrahlung. If this thin-source thermal-bremsstrahlung spectrum is extrapolated back to optical frequencies, the predicted visible intensity is a factor of 4 above the observations. This result is virtually identical with the experiment of 1967 May 18 (Chodil *et al.* 1968) in which an X-ray temperature of $KT = 7 \pm 1$ keV was measured while the source was at $B =$ 12.83. From these data a model source was derived which was a plasma cloud of small dimension, $R \approx 10^9$ cm, and high electron density, $= 10^{16}$ electrons cm^{-3}. This cloud was transparent to X-rays but semiopaque (through free-free absorption) to optical radiation. Thus, self-absorption in the source, together with interstellar extinction, accounted for the optical intensity being less than the bremsstrahlung prediction.

The comparison we wish to make here will not fully utilize this model. The total flux of X-ray energy from the source can be derived from a small extrapolation of the X-ray data. All data are consistent with the total energy in the X-ray region being greatest when the object is brightest.

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II. ROCKET INSTRUMENT

The X-ray detector consisted of a collimator, a NaI(Tl) crystal, and a photomultiplier surrounded by an anticoincidence shield. The detector and rocket payload have already been described in detail (Harri, McGee, and Toor 1969). The detector was sensitive to X-rays with energies between 4 and 70 keV. The rocket was a single-stage Sandhawk and was launched from Tonopah, Nevada (37°.9 latitude, 116°.5 W longitude), 1968 August 22 at 21:48 PDT. Apogee was 187 km. The payload spun at 3.7 rps about its axis of symmetry and precessed around a cone with a 9° half-angle. The payload was recovered after the flight. All data were telemetered to ground during the flight. The rocket carried a small three-axis gyro which measured aspect to within an accuracy of about $\pm 2°$. An attempt was made to point the detector at Cyg X-1 during the first 2 min of flight. This was unsuccessful because of the unexpected large precession angle. During the last 2 min, the detector scanned the horizon and clearly saw the strong Scorpius source. Detector collimation was 25° full width at half-maximum (FWHM) in azimuth and 36° FWHM in elevation.

The X-ray collimator was a silver disk $\frac{1}{16}$ inch thick and slightly larger in diameter than the NaI(Tl) crystal. It was mounted on a rotatable shaft which would be turned in 90° increments during the flight. On one edge of this shutter, a collimated ^{181}W calibration source ($h\nu = 57.5$ keV) was installed. Prior to launch and during the initial acceleration, the shutter was in an open position with the calibration source directed at the detector. After leaving the atmosphere, the shutter was rotated 90°, removing the calibration source and blocking off all X-rays incident on the detector through the front aperture. With the shutter in this position, a measurement of the detector's inherent background and the cosmic-ray induced background was made. After the nose cone was jettisoned, another rotation of the shutter opened the detector aperture, pointing the calibration source away from the detector. In this configuration, data were acquired on Sco X-1 and the diffuse background as the spinning rocket caused the detector to scan the horizon. Upon reentry into the atmosphere, two more rotations provided another measure of the cosmic-ray induced background and a post-flight calibration of the X-ray detector.

III. DIFFUSE BACKGROUND

Figure 1 presents the diffuse X-ray background spectrum. The circles represent the differential counting rate (counts keV^{-1} cm^{-2} sec^{-1} sterad^{-1}), and the crosses represent the photon spectrum. The latter points have been corrected for the detector efficiency and resolution. The detector resolution was good, comparable to the energy intervals chosen for analysis, and there were no large discontinuities in the detector efficiency as a function of energy. Thus, a more exact analysis (Grader *et al.* 1970) to derive the photon spectrum is unnecessary. The error bars are 1 sigma, and represent the uncertainty in efficiency, resolution, and counting statistics. These data come from a region 30° × 30°, centered at a point R.A. $13^{h}20^{m}$, decl. 24°. The solid line is a least-squares fit to the data and is described by: $N_p = 17.1\,(h\nu)^{-1.8}$ where N_p is in photons keV^{-1} cm^{-2} sec^{-1} sterad^{-1}, and $h\nu$ is in keV. Agreement with other experiments (Seward *et al.* 1967; Gorenstein, Kellogg, and Gursky 1969) is satisfactory.

IV. OPTICAL OBSERVATIONS OF SCO X-1

Optical measurements of Sco X-1 were made at Cerro Tololo Inter-American Observatory with the 36-inch reflector and at Lick Observatory with the 24-inch reflector. Photometric techniques and equipment were similar to those used in the past (Hiltner and Mook 1967).

Figure 2 presents the optical intensity in B for Sco X-1 on August 23 from $03^{h}53^{m}$ to $06^{h}00^{m}$ U.T. Uncertainty in the measured B-magnitude is estimated as ± 0.02 mag. The X-ray data were acquired between $04^{h}52^{m}$ and $04^{h}54^{m}$ U.T. The optical data prior to the rocket launch were taken at Cerro Tololo. Observations there were terminated at 04^h34^m U.T., when the setting source became so low in the sky as to make the data unreliable. The data after 04^h56^m U.T. were taken at Lick where twilight prevented observation before this time. Thus, the rocket flight occurred during a gap in optical coverage.

The source was most probably steady during this time, so we take the closest observation (actually taken 3 min after the rocket data) as giving the optical intensity during the X-ray measurement. B was 12.97 $\pm$ 0.02 mag.

At Lick Observatory the transformation constants relating the 24-inch system with the standard *UBV* system were obtained between 03^h59^m and 04^h44^m U.T. The transformation constants were determined by using the Standard Cluster IC 4665, with BD $+5°3483$ as the local reference. Extinction was calculated by following this star down through increasing air mass.

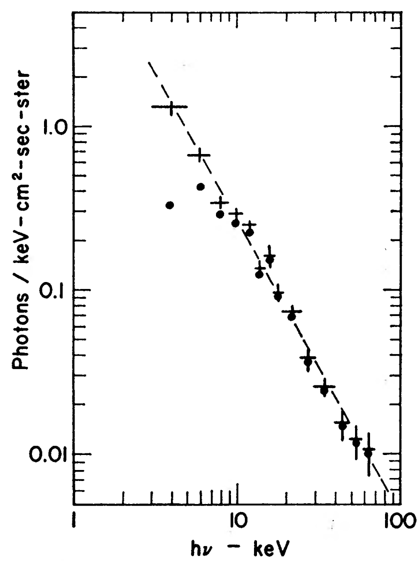

Fig. 1.—Diffuse cosmic X-ray background. *Circles*, data before correction for resolution and efficiency. *Crosses*, corrected data. *Dashed line*, least-squares fit to these data points.

The Sco X-1 comparison star was taken to be BD $-15°4301$. It is located within 8 min of arc of Sco X-1. The color indices for BD $-15°4301$ and the delta values (Sco X-1 minus BD $-15°4301$) were measured at 04^h54^m and 05^h36^m U.T. The color indices for Sco X-1 at 04^h54^m U.T. were found to be: $B - V = 0.23 \pm 0.03$ mag and $U - B = -0.79 \pm 0.03$ mag. The Lick observations were made through an air mass ranging from 2.3 to 2.9.

The data show a fluctuation (or flare?) of about 0.1 mag occurring 10 min after the rocket flight.

V. X-RAY OBSERVATION OF SCO X-1

The azimuthal distribution of the X-ray data taken while the detector scanned the horizon has only one predominant feature: the strong source Sco X-1. Part of the scan, corresponding to the detector pointing out of the plane of the Galaxy, was chosen as a background region. This region was about 30° by 30°, and contained the North Galactic Pole. The data from Sco X-1 were corrected for electronic dead time, and the background was subtracted. These data were then corrected for pointing error, efficiency, and resolution. There could be a 10 percent contribution in these data from unresolved sources toward the galactic center.

The optical and X-ray data are shown in Figure 3. The solid line is a thermal-brems-

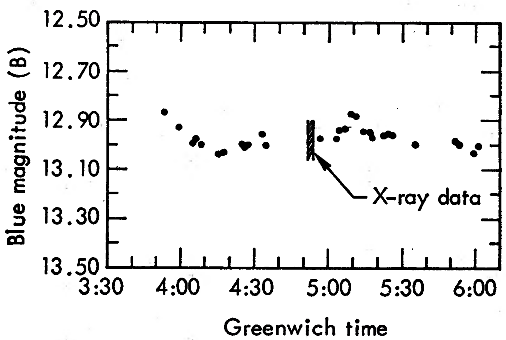

FIG. 2

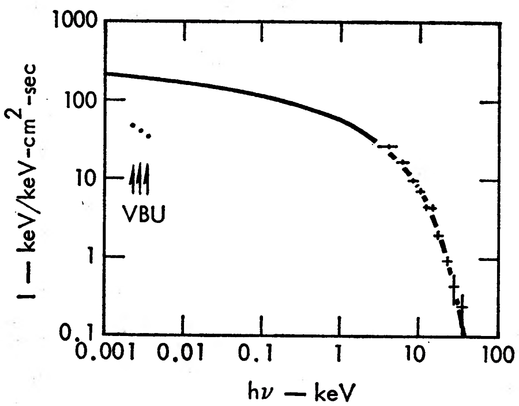

FIG. 3

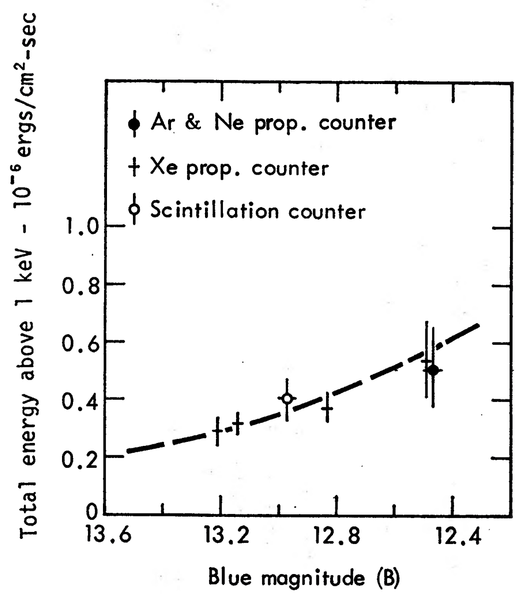

FIG. 4

FIG. 2.—Optical intensity in B versus time for 1968 August 23.

FIG. 3.—Sco X-1 spectrum. *Solid line*, thermal-bremsstrahlung spectrum with a temperature of 7 keV.

FIG. 4.—Total X-ray energy above 1 keV versus B-magnitude. Dashed line illustrates an intensity which increases linearly with B.

strahlung spectrum with a temperature KT of 7 keV. The bremsstrahlung spectrum was calculated by using the method of Chodil *et al.* (1968). An energy-dependent Gaunt factor was used. The error bars are 1 sigma and represent uncertainty in efficiency, resolution, and counting statistics. Above 10 keV the indicated uncertainties are due to statistics only.

VI. COMPARISON WITH PREVIOUS OBSERVATIONS

Is there any significant connection between the X-ray and optical radiation from Sco X-1? Figure 4 is a plot of X-ray energy versus blue magnitude as observed during the six rocket flights. Total energy was determined by fitting thin-source thermal-bremsstrahlung curves to the X-ray data and integrating under this curve from $h\nu = 1$ keV to ∞. Since observations show a turnover in the spectrum below 1 keV (Grader *et al.* 1969) and since it is possible that this is a characteristic of the source itself, we have chosen to extrapolate the X-ray spectrum only to 1 keV. If the integration is continued to $h\nu = 0$, the correlation of Figure 4 is still valid. The uncertainties are due to the absolute uncertainty in the measurement of the X-ray flux and to the uncertainty in the plasma temperature used to fit the data. The dashed line shows an energy linearly dependent on B.

By using the previously discussed model for the source, a radius and density can be derived for the plasma cloud to fit each of the six observations. There are no obvious correlations between these parameters and the B-magnitude or between the temperature and the B-magnitude. Indeed, since the optical energy radiated is about 10^{-3} of the X-ray energy, it is surprising to find a correlation at all. The data points in Figure 4 are based on the assumption that the source mechanism is thermal bremsstrahlung. We seem to be measuring an effect which is not far from the basic uncertainties of the X-ray observations, so the linear relationship is certainly not proven by the data points. One might equally assume an approximately steady X-ray emission that increases only when B is brighter than 12.5 or 12.6 mag.

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