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THE X-RAY, OPTICAL, AND RADIO BEHAVIOR OF SCORPIUS X-1: THE 1972 COORDINATED OBSERVATIONS

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ABSTRACT

We present the results of a 10-day observation of Scorpius X-1 involving seven optical stations, NRAO, and the MIT experiment on the OSO 7 satellite. The source exhibits all of its characteristic variability, including flares and quiescent periods. There is clear evidence for an X-ray–optical correlation in that X-ray activity occurs only where the object is brighter than $m_B \approx 12.7$. However, detailed comparisons of X-ray and optical flares do not show a strict correlation between the intensities, with the exception of one $\sim$20-minute X-ray flare which lags 2 to 3 minutes behind a triple optical flare of similar overall duration. There is no apparent correspondence between two radio flares observed and the shorter wavelength activity.

Subject headings: radio sources, variable — variable stars — X-ray sources

I. INTRODUCTION

Scorpius X-1 shows erratic variability, with time scales ranging from seconds to days, and at wavelengths from the hard X-ray to the radio (see previous paper [Bradt *et al.* 1975] for a review). This variability takes several forms, including well-defined flares found first in the optical emission (Sandage *et al.* 1966) and later in the X-ray (Lewin, Clark, and Smith 1968) and radio (Ables 1969). Several attempts have been made to study Sco X-1 simultaneously in different spectral regions to search for correlations between flares and other features, and thereby to determine the underlying emission mechanism (see Bradt *et al.* 1975). While several phenomenological models have been formulated using these data (e.g., Chodil *et al.* 1968; Neugebauer *et al.* 1969; Kitamura *et al.* 1971; Hayakawa, Kasahara, and Matsuoka 1974; Ramaty, Cheng, and Tsuruta 1974), no systematic understanding has yet been achieved. It has been hoped that if more detailed and extensive simultaneous observations were performed, further clues as to the nature of Sco X-1 might be revealed. The previous papers (Mook *et al.* 1975; Bradt *et al.* 1975) report new results from two simultaneous observations. In this paper we present the results of a third program in which we monitored Sco X-1 at X-ray, optical, and radio wavelengths for 10 days in 1972 June in a world-wide effort to obtain nearly continuous coverage.

II. X-RAY OBSERVATIONS

The X-ray observations were performed with the MIT detectors on the OSO 7 satellite (Clark *et al.* 1973). The data presented here are from an argon-filled proportional counter sensitive from 3 to 10 keV with 3° (full width at half-maximum) collimation. Each X-ray data point represents an average of 95 samples of the source intensity equally distributed over an $\sim$190 s interval, giving a total effective observation time of $\sim$1.4 s.

The data analysis procedure is the same as that described by Canizares *et al.* (1973). Briefly, the raw counts are first adjusted for scaler overflow caused by the high counting rate of Sco X-1, and then fitted to the expected point-source response function plus a background. The resultant X-ray flux from Sco X-1 is shown in figure 1. The vertical length of each data

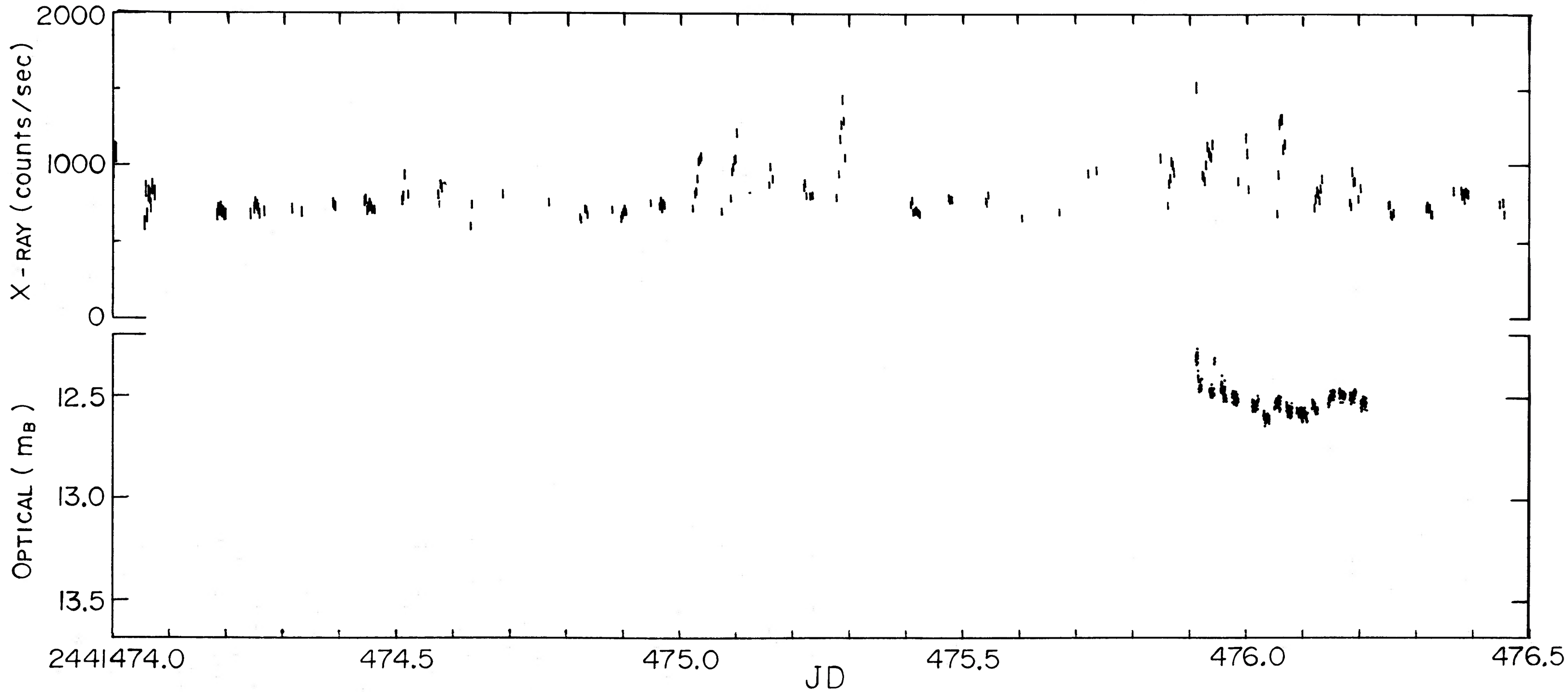

FIG. 1*a*

FIG. 1.—The X-ray counting rate (3–10 keV), the optical *B* magnitude, and the radio intensity in millijanskys for Sco X-1 as a function of Julian day (1000 counts $s^{-1} \approx 32$ photons $cm^{-2}\ s^{-1}$ as described in § II and 1 mJy $= 10^{-29}$ W m^{-2} Hz^{-1}). Gaps in the X-ray data are caused by Earth occultations and data losses. The X-ray error bars show 1 σ statistical uncertainties.

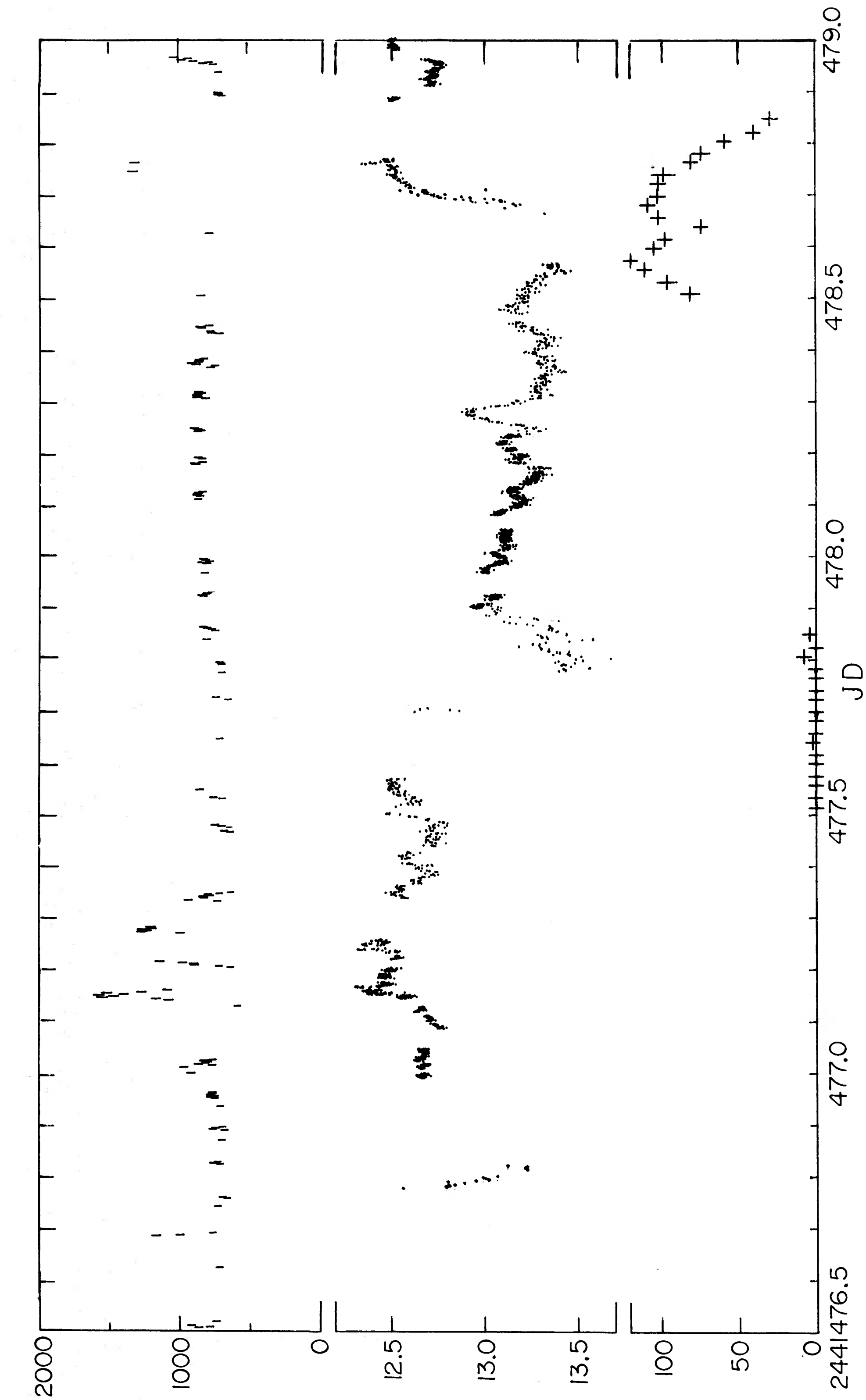

FIG. 1b

FIG. 1.—*Continued*

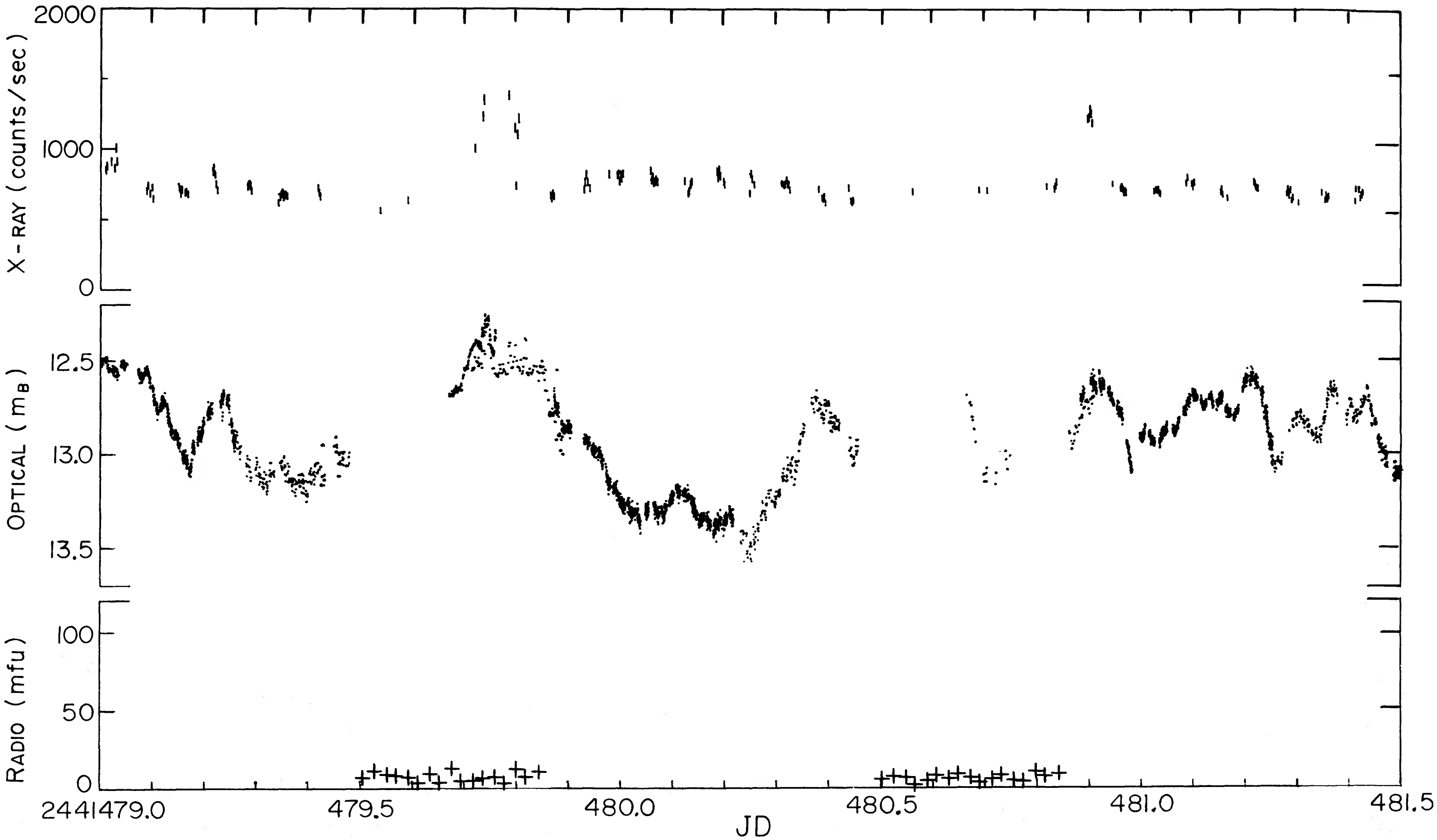

FIG. 1c

FIG. 1.—*Continued*

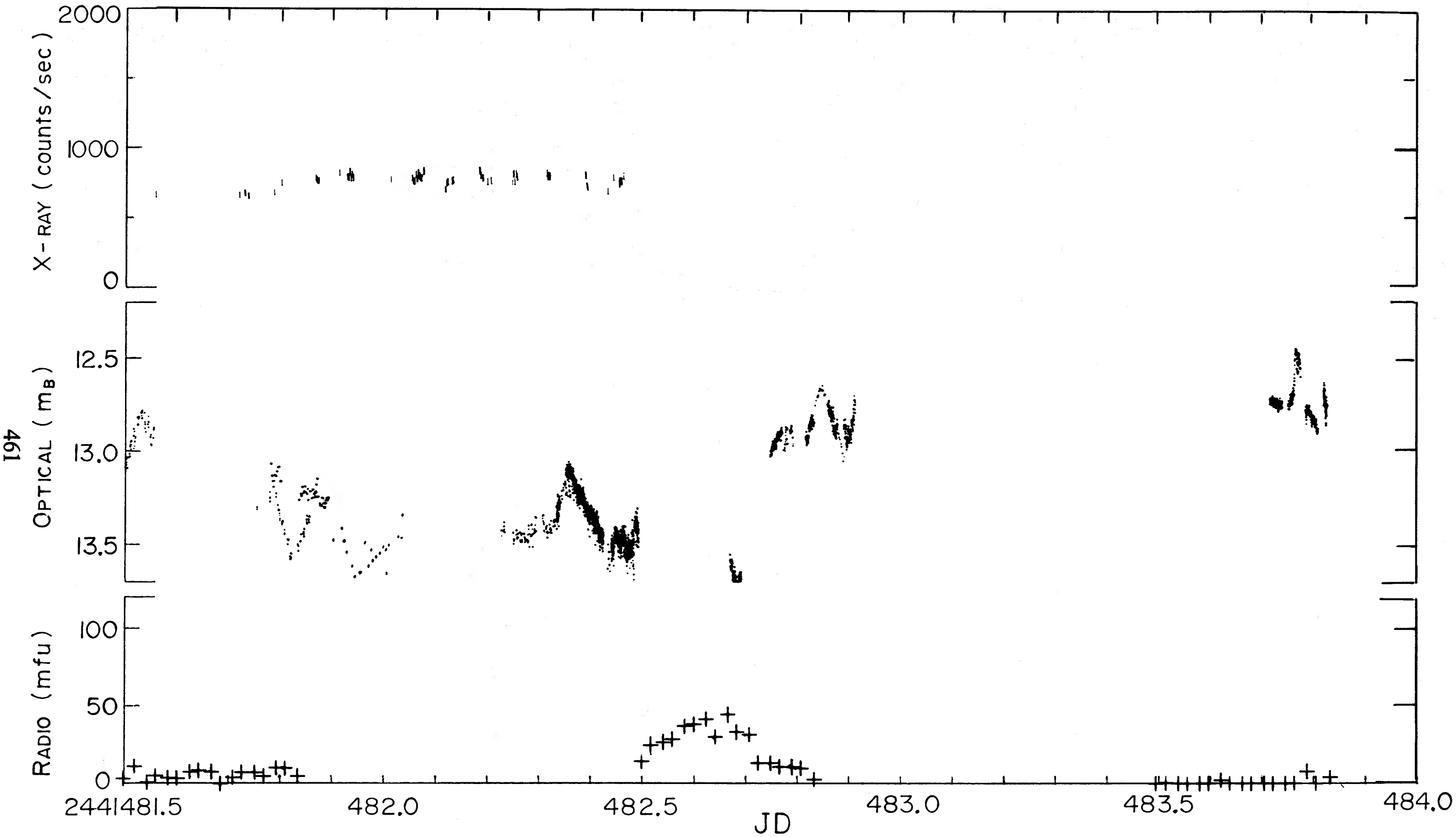

FIG. 1d

FIG. 1.—*Continued*

TABLE 1

PARTICIPATING OPTICAL OBSERVATORIES, ASTRONOMERS, AND INSTRUMENTS

Observatory, Site	Observers	Telescope	Filter	Integration Time	Comments
Kitt Peak National Observatory, Tucson, Arizona	J. C. G.	41 cm	*B*	~60 s	Occasional Clouds.
Leiden Southern Observatory, Broederstroom, Transvaal	A. M. vG.	91	Walraven*	30	5-Color transformed to *B*. Some haze on JD 2,441,479.4 and 480.4.
Mauna Kea Observatory, Hawaii	D. E. M., C. R. C.	61	*B*	30	Some cirrus throughout.
McDonald Observatory, Texas	T. J. M., G. G., P. A. vB.	76	*B*†	20	56DVP photomultiplier.
University of Michigan Observatory, Ann Arbor, Michigan	W. A. H.	132	*B*	~60	
Siding Spring Observatory, Coonabranbran, N.S.W., Australia	C. I., D. B.	41	*B*	20	A few clouds at JD 2,441,475.0.
Florence and George Wise Observatory, Mitzpeh Ramon, Israel	A. F., G. E. S.	102	*B*†	10	S-20 photocathode with *B* filters.

* Walraven and Walraven 1967.

† See text.

point shows the 1 σ statistical uncertainty. (For a thermal bremsstrahlung spectrum of $kT = 5$–10 keV, a counting rate of 1000 counts s^{-1} implies an incident photon flux of $\sim 32\ cm^{-2}\ s^{-1}$ [3–10 keV], and this value is insensitive to fluctuations of kT within the assumed range.) The clumping of points in the X-ray portion of figure 1 reflects the 93-minute orbital period of the satellite with gaps due to Earth occultations of the source. Other gaps are due to the rejection of data heavily contaminated by noise from trapped particles and to telemetry and data-handling losses.

III. OPTICAL OBSERVATIONS

The optical monitoring of Sco X-1 was carried out at seven observatories around the world to provide a nearly continuous record of the source activity. Table 1 lists the participating stations and observers and their equipment. Most observers used the standard *B* filter of the *UBV* system. At McDonald and Wise observatories the photometers and data reduction techniques were not standard, which resulted in an apparent normalization discrepancy between data taken at those stations and those collected elsewhere at the same times. We applied arbitrary normalization factors to the McDonald and Wise data to bring these measurements into agreement with the others. With these exceptions, data from overlapping observations were in reasonable agreement. At the Leiden Southern Observatory, data were collected in the five-color system (Walraven and Walraven 1960) and transformed to *B* magnitudes.

Figure 2 shows the times of the contributions of each site to the data of figure 1. The weather conditions encountered by each observer are briefly noted in table 1. In a few cases, listed observations made through haze or high cirrus clouds were used in the absence of other measurements. Data taken under poor conditions or with uncertain normalization were not used if other measurements were available.

Two of the observations reported here have been presented elsewhere (Moffett, Grupsmith, and Vanden Bout 1973; Frohlich 1973).

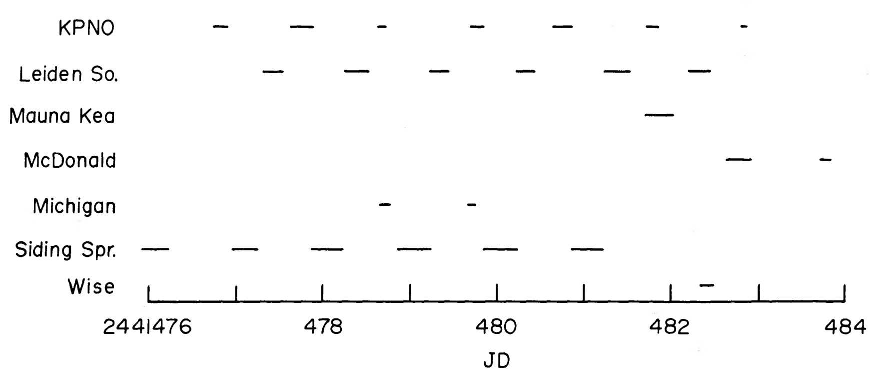

FIG. 2.—Times during which each observatory collected data used in fig. 1

IV. RADIO OBSERVATIONS

The radio observations of Sco X-1 were made with the three-element interferometer at the National Radio Astronomy Observatory (by J. H. S. and G. T. M.). Data were collected simultaneously at 3.7- and 11.1-cm wavelengths, although we present only the latter here. The radio flux levels are plotted in figure 1 and refer only to the central, active component of Sco X-1 (Hjellming and Wade 1970). A full report of the observations is given by Spencer and Murthy (1973).

V. RESULTS

Figure 1 shows the X-ray optical and radio emission of Sco X-1 as a function of time from JD 2,441,474.0 to 484.0 (1972 June 5.5 to 15.5). All of the previously reported characteristic fluctuations at each wavelength can be seen in this figure (see Bradt *et al.* 1975): namely, the X-ray data show quiescent periods, active periods, and flares; the optical data show low states, high states, flares, and other activity; and the radio data reveal quiet times and two moderate flares.

We note the following features:

1. Around JD 2,441,476.0, there is considerable X-ray activity including at least one sizable flare with no optical counterpart. The optical brightness is above the flare threshold of $m_B \approx 12.6$ found by Hiltner and Mook (1967).

2. Around JD 2,441,477.2, X-ray and optical activity coincide. This region of figure 1 is expanded and shown in figure 3. There is a prominent triplet of optical flares with amplitudes of $\sim$0.15 mag and time scale of 2 to 3 minutes. This is very typical of the behavior of Sco X-1 (Hiltner and Mook 1967). The X-ray intensity shows a characteristic flare occurring at the same time. The resolution of the OSO 7 is not adequate to show time structure in the X-ray emission comparable to that in the optical, but it is sufficient to rule out a one-to-one correspondence between the flares in these two spectral regions. To allow a detailed comparison, we have replotted the data for this flare with the optical measurements averaged into 3-minute intervals corresponding to the X-ray data and presented with an arbitrary linear intensity scale. These are shown in figure 4. Seen now with the same resolution, the optical intensity bears a qualitative resemblance to the X-ray signal. However, the initial

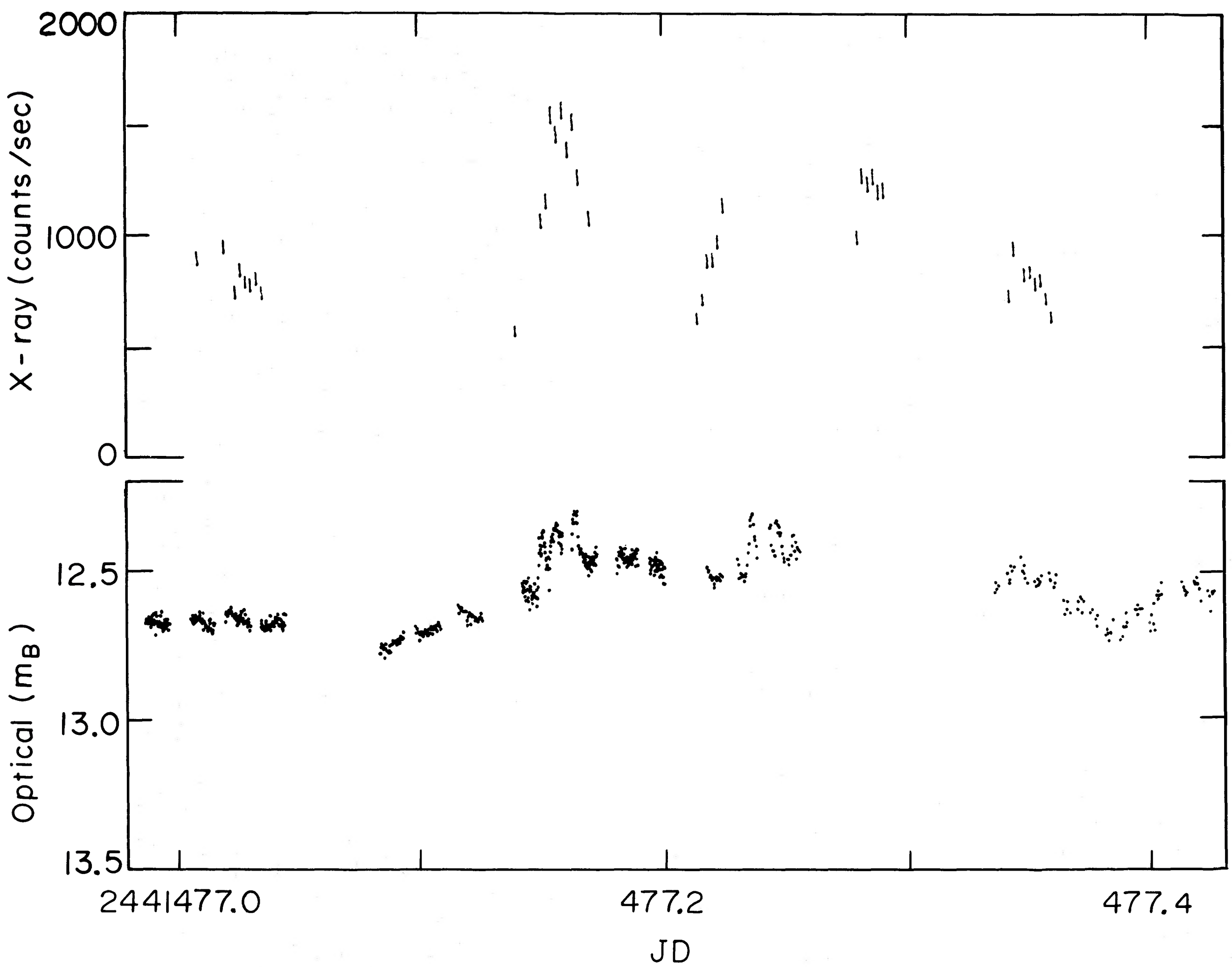

FIG. 3.—A portion of fig. 1 replotted with an expanded time scale

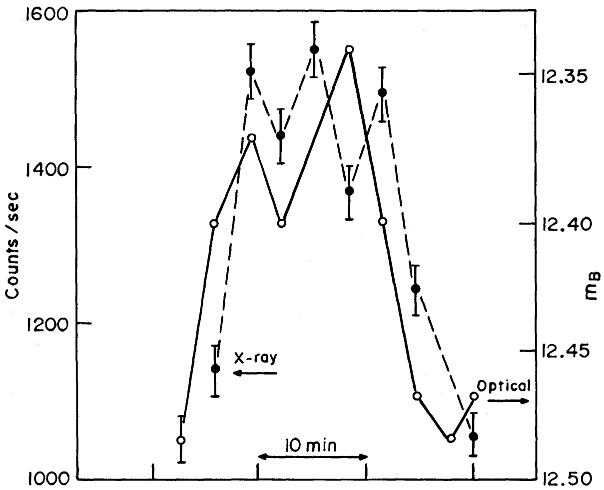

FIG. 4.—X-ray and optical measurements of the flares around JD 2,441,477.15. The optical measurements of fig. 3 have been averaged in 3-minute intervals corresponding to those of the X-ray data and plotted with an arbitrary linear scale (*open circles*).

rise and final fall occur 2 to 3 minutes earlier in the optical than in the X-ray, and the structure within the feature appears different in the two cases.

Shortly after JD 2,441,477.2, there is a rise in X-ray flux by a factor of 2 in ~30 minutes, while the optical remains quiet (see fig. 3). Optical flaring resumes ~10 minutes later at a time of no X-ray coverage.

3. For a full day, from JD 2,441,477.4 to ~478.5, Sco X-1 is quiescent in X-rays, with only a slow overall brightening and then fading (fig. 1). The optical signal shows activity with time scales of tens of minutes to hours, with a prominent brightening at JD 2,441,478.3. The radio observation made during this time shows the source to be quiet. An overall decline of the optical intensity with an increase in X-ray emission as seen here is a quiescent-period characteristic noted by Evans *et al.* (1970).

4. At JD 2,441,478.7, the optical intensity rises abruptly, and the object flares. The X-ray data are sparse but indicate some activity. The strongest radio flare we observed, which has a double structure, occurs around this time. Several hours later the X-ray intensity is found to rise with an apparently concurrent optical rise.

5. At JD 2,441,479.7, optical flaring and X-ray activity coincide, but the data are too sparse to allow a detailed comparison. There is no detectable radio signal.

6. For nearly three days, from JD 2,441,479.7 to 482.5, the X-ray output is generally steady without apparent activity, except for a single factor of 2 enhancement. The optical data show very erratic behavior for this entire period. The X-ray enhancement comes at a peak of the optical activity, but another optical peak $0^d.3$ later seems to have no X-ray counterpart. There is no radio activity seen during this interval.

7. After JD 2,441,482.5, the X-ray coverage ceases and the optical data are sparse. It appears that the optical intensity rises suddenly at JD 2,441,482.7, during the last stages of a radio flare.

We note that our data give no indication of the $3^d.9$ binary period proposed by Lyutyj and Efremov (1974), which implies minima at JD 2,441,476.1, 480.0, and 484.0. An analysis of the $0^d.787313$ period of Gottlieb, Wright, and Liller (1974) will appear elsewhere.

VI. CONCLUSIONS

The behavior of Sco X-1 in the X-ray, optical, and radio shows a high degree of complexity with a tantalizing but still inconclusive tendency for the X-ray and optical activity to be correlated. As noted by previous observers (Gursky 1973; Mook *et al.* 1975; Bradt *et al.* 1975), the correlation is between the level of X-ray activity and the optical magnitude, rather than between the instantaneous or delayed intensities at the two wavelengths. This is shown clearly in figure 5, in which the X-ray intensity is plotted against the optical magnitude. Points are included only when optical data are available for times within the 3-minute resolution of the X-ray measurement. The most active X-ray emission occurs when $m_B \lesssim 12.7$, which is also the requirement for optical flaring (Hiltner and Mook 1967). On the other hand, we have noted numerous cases of uncorrelated activity with no apparent systematic repeatability. In particular, we have observed X-ray flares without optical counterparts, and vice versa. The one clear case of an X-ray flare trailing ~2–3 minutes behind a triplet of ~3-minute optical flares may be characteristic of the source—previous observations of simultaneous flares lack the timing accuracy to show this effect (Hudson, Peterson, and Schwartz 1970; Pelling 1973).

For comparison with other data, we show in figure 6 the brightness histograms for the X-ray and optical

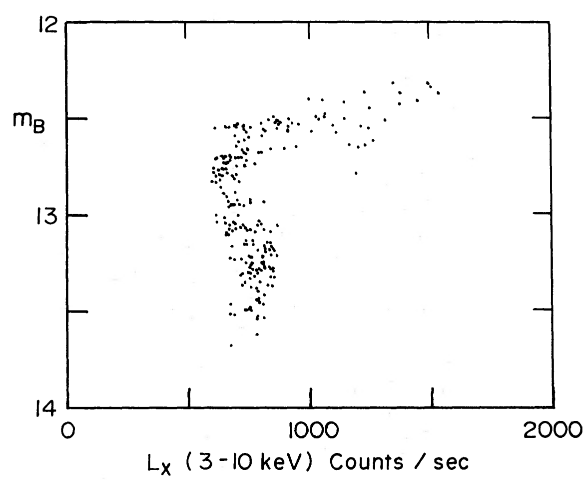

FIG. 5.—Optical *B* magnitude plotted versus X-ray counting rate (3–10 keV) for those times when simultaneous observations were made. Each point represents one X-ray measurement from fig. 1 and the corresponding optical intensity averaged over 3 minutes.

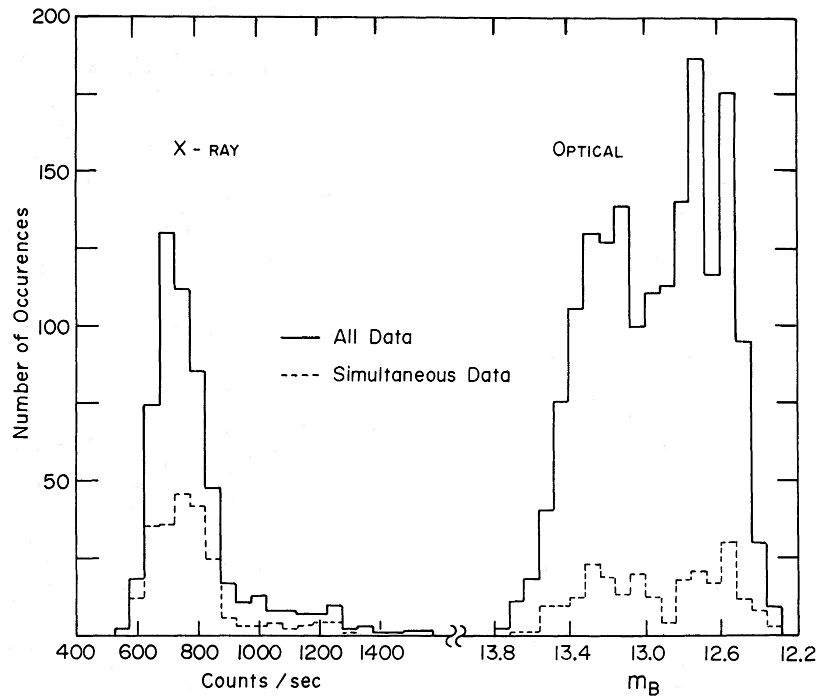

FIG. 6.—Histograms of the number of times a particular X-ray or optical intensity was measured. The solid lines correspond to all the data, the dashed lines to simultaneous portions of the data used in fig. 5. The optical measurements are averaged in 3-minute intervals.

data. These are similar to those obtained by others (Hiltner and Mook 1967; Canizares *et al.* 1973; Pelling 1973; Mook *et al.* 1975; Bradt *et al.* 1975). Figure 6 also shows the histograms for that portion of the data which were simultaneous and included in figure 5. It is clear that the simultaneous data represent a reasonable sampling of all states of the source.

The two radio flares shown in figure 1 occurred near times of large increases of optical luminosity (factors of ~ 2 in ~ 1–1.5 hours). However, the data are much too sparse to indicate any meaningful correspondence between optical and radio emission, and other observations tend to show no correlation (Lampton *et al.* 1971; Bradt *et al.* 1975). There is no apparent X-ray–radio correlation, which again is consistent with other results (Canizares *et al.* 1973; Bradt *et al.* 1975).

Several authors have shown that the optical continuum and the X-ray flux of Sco X-1 are consistent with emission from an isothermal plasma of $\sim 10^{-8}$ to 10^{-9} cm radius with electron densities of $\sim 10^{16}$ cm^{-3} (Chodil *et al.* 1968; Neugebauer *et al.* 1969; Kitamura *et al.* 1971; Hayakawa, Kasahara, and Matsuoka 1974). It is clear from our data and from those of the other simultaneous observations (Mook *et al.* 1975; Bradt *et al.* 1975) that the dynamics of Sco X-1 are much more complex than these models indicate. The facts that large changes in optical luminosity can occur while the X-ray flux is nearly constant and that X-ray fluctuations occur without corresponding optical features argue for a separation of the regions responsible for at least a portion of the X-ray and optical emissions. A separation is already recognized as necessary to explain the radio data (Ramaty, Cheng, and Tsuruta 1974). On the other hand, the clear correlation between times of X-ray and optical activity implies that some connection exists between the optical and X-ray emission processes. The 2- to 3-minute delay between an optical and X-ray flare may represent a physical separation, although the propagation velocity and thus the characteristic length are not known.

It is unfortunate that the extensive data presented here and by Mook *et al.* (1975) and Bradt *et al.* (1975) still do not indicate how the simplified models might be improved to explain the complexities of Sco X-1. Our observations do indicate that future programs should try to achieve simultaneous coverage with higher time resolution rather than continuous coverage over many days. A more careful analysis of coincident flares and a study of simultaneous X-ray and optical spectroscopy may provide new clues to the nature of this source. In this regard the SAS-C satellite, being constructed by MIT for launch in 1975, contains a Sco X-1 monitor experiment well suited to carry out further observations of this kind.

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