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RAPID X-RAY AND OPTICAL FLARES FROM SCORPIUS X-1[1]

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ABSTRACT

We report the discovery of 1 s time structure in X-ray flares from Sco X-1 and simultaneous optical flares with time structure no faster than 20 s. This decreases by a factor of 10 the shortest reported time scale in the X-ray emission of Sco X-1, but is consistent with the parameters of the standard plasma model for Sco X-1 ($R = 19^9$ cm, $T = 5 \times 10^7$ K, and $N_e = 10^{16}$ cm^{-3}). Different mechanisms for the production of X-ray flares and optical flares are suggested by the disparity in the fastest X-ray and optical time scales. The production of optical flares by reprocessing on the surface of the binary companion of Sco X-1 is ruled out by the X-ray/optical flare time delay.

Subject heading: X-rays: sources

I. INTRODUCTION

Since Sco X-1 was discovered (Giacconi *et al.* 1962) and its optical counterpart identified (Sandage *et al.* 1966), the X-ray and optical variability and their correlation have been studied extensively. In 1967 Lewin, Clark, and Smith (1968) made the first observation of X-ray brightness variability in an extra-solar X-ray source when they observed an X-ray flare of 30 minute duration from Sco X-1. One year earlier Sandage *et al.* (1966) had observed optical flickering characteristic of old novae from the optical counterpart of Sco X-1. The most rapid reported X-ray time scale of variability in Sco X-1 is 10–20 s which characterizes the width of the flares (Kestenbaum *et al.* 1971; Griffiths and Cooke 1972; Ilovaisky *et al.* 1980). Similar optical time scales have been reported (Westphal, Sandage, and Kristian 1968; Sandage, Westphal, and Kristian 1969; Kestenbaum *et al.* 1971; Robinson and Warner 1972). Searches for X-ray variability in the range 10 ms–1 s have not been successful (Friedman *et al.* 1969; Angel, Kestenbaum, and Novick 1971; Boldt, Holt, and Serlemitsos 1971; Holt *et al.* 1973). However, these searches were based on necessarily short duration sounding rocket flights and ~ 100 cm^2 detectors and thus may have missed episodic or weak, rapid variations.

A complete correlation between the optical and X-ray brightness of Sco X-1 has not been established (Miyamoto and Matsuoka 1977, and references therein). It has been recognized that *states* of optical flaring and of X-ray flaring are coincident when the source is optically bright ($B \lesssim 12.7$; Evans *et al.* 1970; Pelling 1973; Gursky 1973; Matsuoka *et al.* 1974; Bradt *et al.* 1975; Mook *et al.* 1975). Correlated 10 minute flares (Hudson, Peterson, and Schwartz 1970; Pelling 1973; Canizares *et al.* 1975), correlated 20 s oscillations (Kestenbaum *et al.* 1971), and five episodes of correlated flaring (Ilovaisky *et al.* 1980) have been reported. However, examples of uncorrelated optical and X-ray flares also have been reported (Canizares *et al.* 1975; Ilovaisky *et al.* 1980).

It is the purpose of this *Letter* to communicate the detection of X-ray variability that occurs on a time scale approximately 10 times faster than previous studies have recognized and to report simultaneous optical observations which show, on a time scale of 20 s or longer, an extremely good correlation with the X-ray flares. Our measurements were made during a 1 hour episode of flaring which occurred during a 10 day coordinated world-wide optical/X-ray study of Sco X-1 (Petro 1979). More detailed results on the X-ray, ultraviolet, and optical brightness and spectrum variations and their interrelationships will be presented at a later date.

II. OBSERVATIONS

The X-ray observations of Sco X-1 presented here were carried out with the *SAS 3* X-ray observatory Horizontal Tube Collimator detector (1–12 keV, 1°.7 FWHM), Xenon Tube Collimator detector (8–19 keV, 1°.7 FWHM), Center Slat Collimator detector (1.5–15 keV, 1° × 32° FWHM), and Right Slat Collimator detector (1.5–15 keV, 0°.5 × 32° FWHM) (Lewin *et al.*

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1976; Buff *et al.* 1977). The total collecting area of these detectors is 340 cm^2. The time resolution employed during our analysis was 0.83 s. These pointed mode observations were conducted 1 month before *SAS 3* reentered the atmosphere. Atmospheric forces on the satellite produced a variation of 1°5 full amplitude in the z-axis direction, which caused a sinusoidal variation in the y-axis collimator transmission at a period of approximately 2800 s (one-half the satellite orbital period). The collimator transmission variation has not been removed from the data presented here, but it will have a negligible effect on the 1–100 s time structure to be discussed. The maximum effect of the modulation on the data presented here is a 0.1% per second linear brightness change with a 1400 s time scale, which could produce the linear trends evident in Figure 1*a*.

The optical data were obtained with the 100 inch (2.5 m) Hooker telescope on Mount Wilson through thin cirrus clouds. The photoelectric observations were made in the Johnson *B* band with a 17″ diameter diaphragm. A pulse counting data system wrote onto magnetic tape the number of detected photons per 10 ms interval. The start time of individual 10.7 minute observing runs was manually recorded, and thus there is a possibility that occasional 1 s absolute timing errors exist in the optical data. Thus, X-ray/optical flare time delays discussed below will have a systematic uncertainty of 1 s.

Selected segments of the X-ray data are shown in Figure 1. Several rapid events should be noted. Unresolved edges occur in Figure 1*e* at $t = 65$ s and $t = 82$ s. A short duration flare occurs in Figure 1*a* at $t = 106$ s (FWHM = 3 s) and possibly in Figure 1*d* at $t = 160$ s (FWHM = 1.7 s). A sharp dip is superposed on a slow flare in Figure 1*c* at $t = 204$ s. These examples demonstrate that the X-ray flare emission can be fully modulated on a time scale of 1 s, but it is

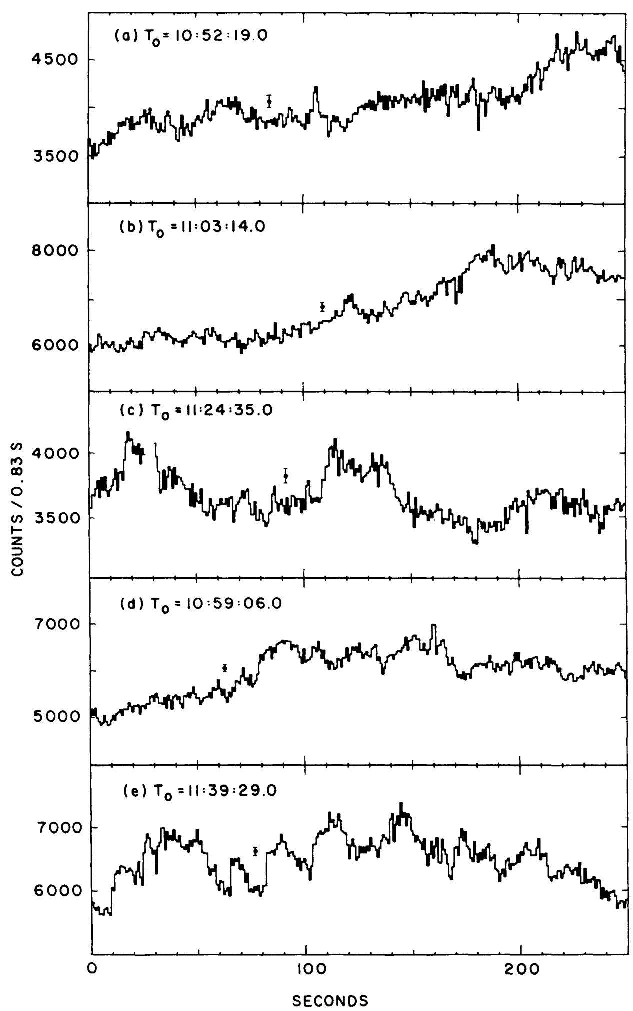

FIG. 1.—Rapid X-ray flare time structure, 1–19 keV. The panels are in order of increasing flare duration. The data epochs are given in the upper left-hand corner of each panel. The time bin size is 0.83 s. Typical Poisson standard deviations are indicated by the plus and minus 1 σ error bars.

possible that the actual variability extends to time scales shorter than the instrumental time resolution of 0.83 s.

An examination of Figure 1 also suggests that two distinct types of flares exist: rapid rise flares and slow rise flares. The rapid rise flares have rise and fall times which range from less than 0.83 s to ~ 3 s and have durations which range from ~ 3 s to ~ 100 s, although the longer duration flares could be characterized as a sequence of flares of shorter duration (e.g., in Fig. 1*d* at $t = 80$–170 s). Slow rise flares have a full width (typically 30–60 s) which is approximately equal to twice the rise time. The flare in Figure 1*c* at $t = 110$ s is an example of a rapid rise flare, whereas the flare at $t = 193$ s of the same figure is an example of a slow rise flare.

It is of interest to note that the flares in Figure 1*e* recur quasi-periodically at a period of ~ 20 s throughout the 4 minute interval. A similar 20 s oscillation was observed by Kestenbaum *et al.* (1971).

Some of the correlated flares observed by us are shown in Figure 2. To aid in judging relative rise times, fall times, and delays, vertical lines have been drawn in this figure at times when a clearly identifiable sharp rise or fall occurs in the X-ray emission.

As found by Ilovaisky *et al.* (1980), there are flaring episodes during which there is a very good correlation between X-ray and optical flares. This is especially true of the isolated, 30 s duration flares in Figure 2*a*. However, the sequence of short duration (10–20 s) flares in Figure 2*b*, beginning at $t = 150$ s, are not individually recognizable in the optical emission. Instead, a single, broad optical flare is present whose duration is the same as that of the duration of the sequence of X-ray flares. Similarly, the rise time (e.g., in Fig. 2*a* at $t = 100$ s) and decay time (e.g., in Fig. 2*a* at $t = 150$ s) of correlated optical flares are 10–20 s, whereas the X-ray flares have rise times and decay times of $\lesssim 3$ s. Qualitatively the optical flares may be described as filtered versions of the X-ray flares where the filter time constant is approximately 20 s.

Although there is considerable smoothing, it can be seen that the optical emission begins to rise within one bin (3.4 s) after the X-ray flare begins. A more accurate determination of the value of the delay between X-ray flare initiation and optical flare initiation would be dependent on the assumed shape of the X-ray-to-optical transfer function. We shall not present such an analysis here, but merely note that a delay of 9 s (which shall be important below) is clearly incompatible with the data, whereas zero delay is consistent with the data.

III. DISCUSSION

We have interpreted the observations presented above within the context of two extant, simple models: one model for the X-ray/optical/IR continuum formation region and the other model for the binary system. The model for the X-ray/optical/IR continuum emission region is a single temperature ($T = 5 \times 10^7$ K), spherical ($R = 10^9$ cm) plasma with an electron scat-

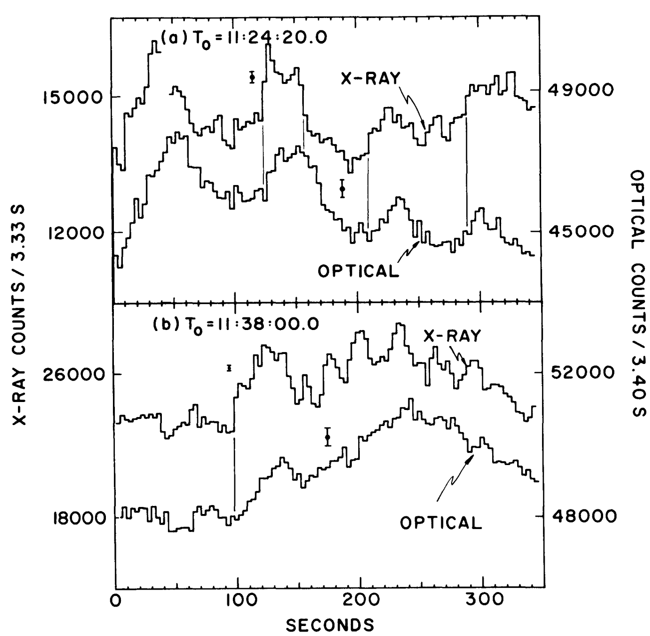

FIG. 2.—Detail of correlated flares. The optical data were obtained with the Mount Wilson 100 inch (2.5 m) telescope through a *B* filter. The X-ray data were obtained with the *SAS 3* X-ray observatory in the energy range 1–19 keV. The time bin durations are 3.40 s for the optical data and 3.33 s for the X-ray data. Vertical fiducial marks are placed at times of sudden X-ray brightness changes. Typical Poisson standard deviations are indicated by the plus and minus 1 σ error bars above each light curve.

tering optical depth $\tau = 10$–20 (Chodil *et al.* 1968; Neugebauer *et al.* 1969; Mark *et al.* 1969; Felten and Rees 1972). The model for the binary system has elements: $P = 0.787313$ days; $M_x = 1.3\ M_\odot$; $M_{\mathrm{opt}} = 0.8$–$1.2\ M_\odot$; $i = 25°$–$30°$; $a = 11$ lt-s; and epoch of X-ray source superior conjunction = JD 2,442,565.94 (Gottlieb, Wright, and Liller 1975; Wright, Gottlieb, and Liller 1975; Crampton *et al.* 1976). Except for the period, these orbital elements result from the interpretation by Crampton *et al.* (1976) that the optical emission-line radial velocities reveal the orbital motion of the neutron star X-ray source.

First, we consider the escape of an infinitesimal pulse of photons from the center of an electron scattering plasma. In the diffusion approximation, the rise time of the pulse escaping from the surface is given by $t_r \approx 0.3\ \tau R/c$, where τ is the optical depth and R is the radius of the plasma sphere (Sunyaev and Titarchuk 1980). If we take a median value of $\tau = 15$ (Lamb and Sanford 1979), then our limit on the fastest observed rise time, $t_r \lesssim 1$ s, requires $R \lesssim 7 \times 10^9$ cm, which is comfortably a factor of 7 greater than the typical model radius given above. Thus, the present observations do not constrain the generally accepted model for the continuum formation region, but an improvement by a factor of 10 in the instrumental time resolution might do so.

If the optical flares originate in the same region as the X-ray flares (as suggested by the single X-ray/optical/IR continuum), then the optical flares should have the same rise time as the X-ray flares, because electron scattering is the dominant source of opacity for both X-ray and optical photons at the temperature and density of the standard model for Sco X-1. The coincident optical flares which we have observed have a rise time at least 10 times longer than that of the X-ray flares and cannot, therefore, be produced in the same region. It would seem plausible that reprocessing at a site other than the X-ray production site is the source of the optical flares. Neugebauer *et al.* (1969) have also noted the necessity of a region other than the X-ray emission region to account for the optical emission lines, which have ionization temperatures 10^3 times less than the X-ray continuum temperature. Laros and Singer (1976) also have suggested a separate scattering region which modifies the thermal bremsstrahlung X-ray spectrum.

Finally, we consider the geometrical delay of the optical flares. At the time of the observations shown in Figure 2, the phase of the system (measured from X-ray source superior conjunction) was 0.50. For photospheric reprocessing, the minimal optical delay (neglecting reprocessing delays) may be calculated using the light travel time to the inner Lagrangian point. If we denote the distance from the X-ray source to the inner Lagrangian point as r_L and the phase with respect to X-ray source superior conjunction as θ, then an optical flare will lag an X-ray flare by at least $t_g = (r_L/c)(1 - \cos\theta\ \sin i)$. For the Crampton *et al.* (1976) model this optical time delay is 8–9 s. Thus, the data of Figure 2 rule out the photosphere of the companion star as the reprocessing site of the optical flares.

An accretion disk, or some other configuration centered on the X-ray source, is consistent with no time delay and is therefore a viable reprocessing site. Detailed consideration of these possibilities must explain the large optical smearing time scale observed by us, taking into account the reprocessing mechanism and the geometry of the reprocessing site. The reprocessing time for the Her X-1/HZ Her system is 0.3 s (Chester 1978), and observations of optical bursts show that the reprocessing time in those systems is less than a few seconds (Grindlay *et al.* 1978; Hackwell *et al.* 1979; Pedersen *et al.* 1981). Furthermore, the X-ray Roche lobe radius of the Crampton *et al.* (1976) model for Sco X-1 is 4.4 lt-s. Thus, we have no natural physical or geometrical explanation for the 20 s Sco X-1 optical smearing time scale.

IV. SUMMARY

Observations of X-ray time structure in Sco X-1 remain consistent with the standard plasma model for Sco X-1. However, coincident optical flares are not consistent with direct emission from the X-ray plasma nor with photospheric reprocessing, but they are qualitatively consistent with reprocessing in an accretion disk or some other configuration centered on the X-ray source.

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