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OF
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Long-Term X-ray Studies of Sco X-1

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ABSTRACT

No modulation of the 3-6 keV x-ray intensity of Sco X-1 at a level of excess of 1% is observed at the optical period of .787313d. Evidence is found for shot-noise character in a large fraction of the x-ray emission. Almost all of the Sco X-1 emission can be synthesized in terms of ~ 200 shots per day, each with a duration of ~ 1/3 day.

Subject headings: x-ray sources -- binaries

I. INTRODUCTION

As Sco X-1 is, by far, the brightest x-ray source in the sky, searches for regularity in its temporal behavior have been undertaken for almost a decade. As yet, no reproducable regularity in x-rays has been observed on any timescale (c.f. Canizares, et al. 1975, Holt, et al. 1973, and included references).

More recently a convincing periodicity of 0.787313d has been discovered by Gottlieb, Wright, and Liller (1975) at optical wavelengths. The modulation amplitude of this effect in the optical is ~ 25%. We report here an upper limit of 1% to any similar variation in x-rays.

The irregular variability of Sco X-1 in x-rays has long been noted, but no quantitative estimate of the extent or timescale of this variability (in general) has been available. The long-duration exposures to Sco X-1 reported here enable us to estimate this variability on timescales of hours or more, and allow for the modeling of the temporal intensity profile of Sco X-1. It is found that a large fraction of the emission from the source can be sensibly associated with shot-like pulses of duration ~ 1/3d.

II. SEARCH FOR PERIODICITY

The present data are obtained with the Ariel-5 All-Sky Monitor, a scanning pinhole camera with efficiency-corrected area of 0.6cm^2 in the band 3-6 keV. The finest temporal resolution available is 100 minutes, during which time the duty cycle for source observation is ~ 1%. Approximately 300 Sco X-1 counts are accumulated in each 100 minute orbit, in a background which is typically < 10 counts. A more extensive experiment description may be found in Holt (1975).

Figure 1 is a fold of one year of single orbit Sco X-1 data at the Gottlieb, Wright and Liller (1975) optical period of 0.787313d. No single sinusoid at any phase with amplitude as large as 1% can be fit to the data. Any modulation of the x-ray intensity at this period must, therefore, be more than an order of magnitude below the corresponding optical modulation.

III. SHOT-NOISE ANALYSIS

The intensity measured each orbit from Sco X-1 is not consistent with a constant average. Some indication of this non-Poisson behavior is evident from Figure 2, where (b) contains a particularly variable sample of single-orbit Sco X-1 data. The intensity never drops substantially below 10 $\text{cm}^{-2}\text{sec}^{-1}$ (3-6 keV) or above ~ 30 $\text{cm}^{-2}\text{sec}^{-1}$ over the first year of Ariel-5 operation (1974 October - 1975 October), although its average value over 3-month intervals decreases monotonically during the year (see Figure 1).

Of particular interest is the fact that intensity variations generally extend over several orbits, indicating that the totality of Sco X-1 variation cannot be ascribed to individual "flares" with duration $\leqslant$ 1 hour.

Terrell (1972) first pointed out that the intensity fluctuations in sources like Cyg X-1 on timescales of < minutes could be reconciled with the mathematical formalism of classical shot-noise. This picture was pursued by Boldt, et al. (1975) and Weisskopf, Kahn and Sutherland (1975), with the result that the major fraction of the emission from Cyg X-1 can be represented by shot-noise with a shot duration of ~ 1/2 sec. Presumably, this timescale is characteristic of the x-ray emitting volume of Cyg X-1, and we attempt here to apply an analogous formalism to data obtained with the Ariel-5 All-Sky Monitor from Sco X-1.

The basic test we apply to the data is the extent to which the source variations, as a function of sampling time, are consistent with the statistical errors. We construct a "variance ratio" V, which is defined:

$$V_t = \left\langle \frac{(I_k - \bar{I})^2}{(\delta I_k)^2} \right\rangle , \qquad (1)$$

where $\bar{I}$ is the mean of the intensity values I_k (each obtained over a sampling time t, and each with statistical error δI_k). The expectation-value-brackets indicate that V_t represents the mean of each of the k values of the bracketed quantity in the total data sample. Clearly, if the scatter of the I_k about $\bar{I}$ is statistical only, $V_t = 1$. Furthermore, if the errors δI_k have been underestimated, $V_t > 1$ but is independent of timescale t.

If we assume that the emission from a source is composed entirely of a constant baseline and a superposition of shots of several durations (τ_i) it may be shown that

$$V_t = \kappa^2 \{1 + \eta \sum_i \frac{f_i^2}{\lambda_i} (A_i)_t\} , \tag{2}$$

where η is the number of counts detected in the smallest sampling interval (t=1), f_i is the fraction of η arising from the i'th variety of shot noise, λ_i is the corresponding shot pulse rate (in units of $(t=1)^{-1}$) of duration τ_i (in units of t=1), and

$$\begin{aligned} (A_i)_t &= 1 \text{ for } t \gg \tau_i, \\ &= \frac{t}{\tau_i} \text{ for } t \ll \tau_i. \end{aligned} \tag{3}$$

κ is a possible correction factor if the statistical error has been incorrectly estimated ($\kappa = 1$ if the error is correct).

The method of investigation then involves an interrogation of three aspects of the V_t distribution. If we assume a Sco X-1 intensity composed of a constant baseline and two shot-noise components, one with $\tau_1 \ll (t=1)$ and one with $\tau_2 \gg (t=1)$, we obtain

$$\begin{aligned} V_1 &= \kappa^2 \{1 + \eta (\frac{f_1^2}{\lambda_1} + \frac{f_2^2}{\lambda_2 \tau_2})\} , \\ V_2 - V_1 &= \kappa^2 \eta \frac{f_2^2}{\lambda_2 \tau_2} , \\ \text{and } V_\infty &= \kappa^2 \{1 + \eta (\frac{f_1^2}{\lambda_1} + \frac{f_2^2}{\lambda_2})\} . \end{aligned} \tag{4}$$

The simultaneous solution of the above yields an unambiguous value of τ_2 (if the model is correct) since η is prescribed by the data, but the other parameters are not uniquely definable. In particular, f_i^2/λ_i is not separable, and cannot be determined independently of κ. We can, however, construct an additional "measurable" quantity similar to equation (1) from adjacent data elements only, i.e.

$$V' = \left\langle \frac{(I_k - I_{k+1})^2}{(\delta I_k)^2 + (\delta I_{k+1})^2} \right\rangle . \qquad (5)$$

This expression reduces to V_1 in the limit of either no shot noise or $\tau \ll (t = 1)$ and has the advantage of being relatively insensitive to variations on time scales much longer than $(t = 1)$.

Figure 3 is the distribution of V_t for $\sim 10^3$ orbits of data obtained between 1974 December and 1975 February. It is clear that no single shot-noise model can explain the V_t distribution because there is no apparent asymptote. Some insight into a possible recovery from this disappointment can be gleaned from Figure 3b, where the four quarters of the 10^3 orbits have each been analyzed separately. Only trial 3 is obviously inconsistent with the $\lambda = 10$, $\tau = 4$ trace of Figure 3a, and the reason may be apparent from Table I. A marked change in the average intensity $\bar{I}$ occurred between trials 3 and 4 (actually during the duration of trial 3). As λ cannot be treated as a variable in the analysis as developed, any local variation in λ outside of Poisson statistics will invalidate the form of equation (1).

In order to determine the possible contribution of an underestimated error, two separate diagnostics were used. Crab Nebula data were analyzed in precisely the same way, with the result that V_t was always < 2, with an average value of ~ 1.3. This is an indication that some unrecoverable systematic errors are present in the data (associated with pointing errors and incorrect accumulation times), but the same value of κ $(\sim \sqrt{1.3})$ may not be appropriate to Sco X-1. A direct test is the value of V', which should be unity for both the limiting cases $\tau << 1$ and $\tau >> 1$. Its value of ~ 4.4 indicates that in no case can the estimated error be incorrect by more than a factor of two, and it is probably much less than that. As we can determine τ_2 independently of κ, however, $4 < \tau_2 < 5$ (a shot duration of $\sim 1/3$ d) is apparently a firm result of this analysis.

We can solve (non-uniquely) for the remainder of the parameters, because κ is estimable and consistency with the data is achievable. If we adopt $1 \leq \kappa \leq \sqrt{2}$, we obtain $.7 \leqslant f_2 \leqslant .9$ for the situation $4 \leq \tau_2 \leq 5$ from V' alone, which is consistent with the overall picture of these long-duration shots dominating the source variation (in this case, f_1 plays no significant role in the determination of V'). The pulse rate λ_2 may vary considerably, ranging from ~ 8 ($f_2 = .7$, $\kappa = 1$) to ~ 27 ($f_2 = .9$, $\kappa = \sqrt{2}$).

IV. SUMMARY AND DISCUSSION

No discernable x-ray modulation of the Sco X-1 intensity is observed at the binary period of 0.787313d, with an upper limit of 1%. The only regularity in the x-ray emission for timescales in excess of a few hours appears to be the consistency of a large fraction of the emission with shot noise. The most likely parameters (in units corresponding to 100 min. orbits) are $\tau_2 = 4.5 \pm .5$, $\lambda_2 = 15 \pm 5$ and $f_2 = .8 \pm .1$. Variations on smaller timescales (or a constant baseline intensity) are not assignable from the present data. It should be noted, however, that "flares" with duration $\leqslant$ 1 hour are explicitly required for complete consistency, with an expected average frequency $\leqslant$ 10 day^{-1} contributing at most a few percent of the total source emission. The average pulse rate λ_2 can remain roughly constant for times of the order of a month (i.e. the actual number of shot pulses per orbit has a Poisson distribution about this mean), but can change by ~ 10% in a time < 1 week. These changes in λ_2, although relatively small, make the V_t distribution uninterpretable for total sample times > 1 month.

The key features of this analysis with respect to a physical interpretation of the parameters are a multiplicity of pulses (i.e. not a single pulse present at one time), and a characteristic time of ~ 1/3d (i.e. one-quarter to one-half of the binary period of the system). With respect to the former feature, the large number of shots present any time (~ 70) imply an emission region which is not well-localized. An accretion disk is the obvious candidate region for such a diffuse phenomenon, but we have no satisfactory a priori reason for expecting the deduced shot frequency. The consistency of the characteristic shot duration with $\leqslant$ one-half the binary period might conceivably be interpreted as a distribution of hot spots which each have duration times longer than 1/3 day, but which are intensity-modulated at the .787d period of the binary system. This would suggest an expected .787 periodicity in the Sco X-1 intensity over a small number of cycles, but no such short-term behavior is apparent in Figure 2b. It would appear, therefore, that ~ 1/3d is the true duration of the x-ray emission pulses.

The "model" we have presented here requires no detailed physical assumptions about Sco X-1: instead, it is a simple mathematical idealization (in terms of constant-amplitude, constant-duration shots) which can synthesize the temporal behavior of the source on timescales $>$ 1 hour. Nevertheless, this overall consistency with a multiplicity of long-duration shots (rather than single flares superimposed on a baseline continuum) may be generally characteristic of accretion sources. Lamb, Pines and Shaham (1975) have suggested that the anomalous rotation period variations in Her X-1 and Cen X-3 may be explainable in terms of shot-like accretion variations in those sources, for example.

Table I

"Measurable" Parameters in Shot-Noise Analysis

Run	V_1	V_2-V_1	Asymptote*	V'	$\bar{I}$
1-4	10.7	4.1	--		17.2
1	8.7	3.6	~24	4.4	17.6
2	10.1	4.6	~23	5.5	17.9
3	9.8	5.1	--	4.3	17.6
4	8.3	4.2	~27	3.5	15.7

*The best value of asymptote is obtained for t between ~3 τ and ~ 1/5 of the total data record t_{max}

Figure Captions

1. Sco X-1 single-orbit data folded modulo .787313d. The trace labelled "total" contains one year (1974 October - 1975 October) of data, while the other four are each approximately one-quarter of the data.
2. Sample Sco X-1 single-orbit data. The first 10^3 orbits in the 90–day interval in a) are used in the shot-noise analysis. The apparent coherence of most intensity variations over several orbits displayed in b) is typical of the total Sco X-1 record.
3. The variance ratio V_t as defined in the text for a) the total 10^3 orbits analyzed, and b) the four quarters of the 10^3 orbit record. The parameters of Table I are extracted from these data. Also shown in a) are the expected V_t for the annoted simple shot-noise cases.

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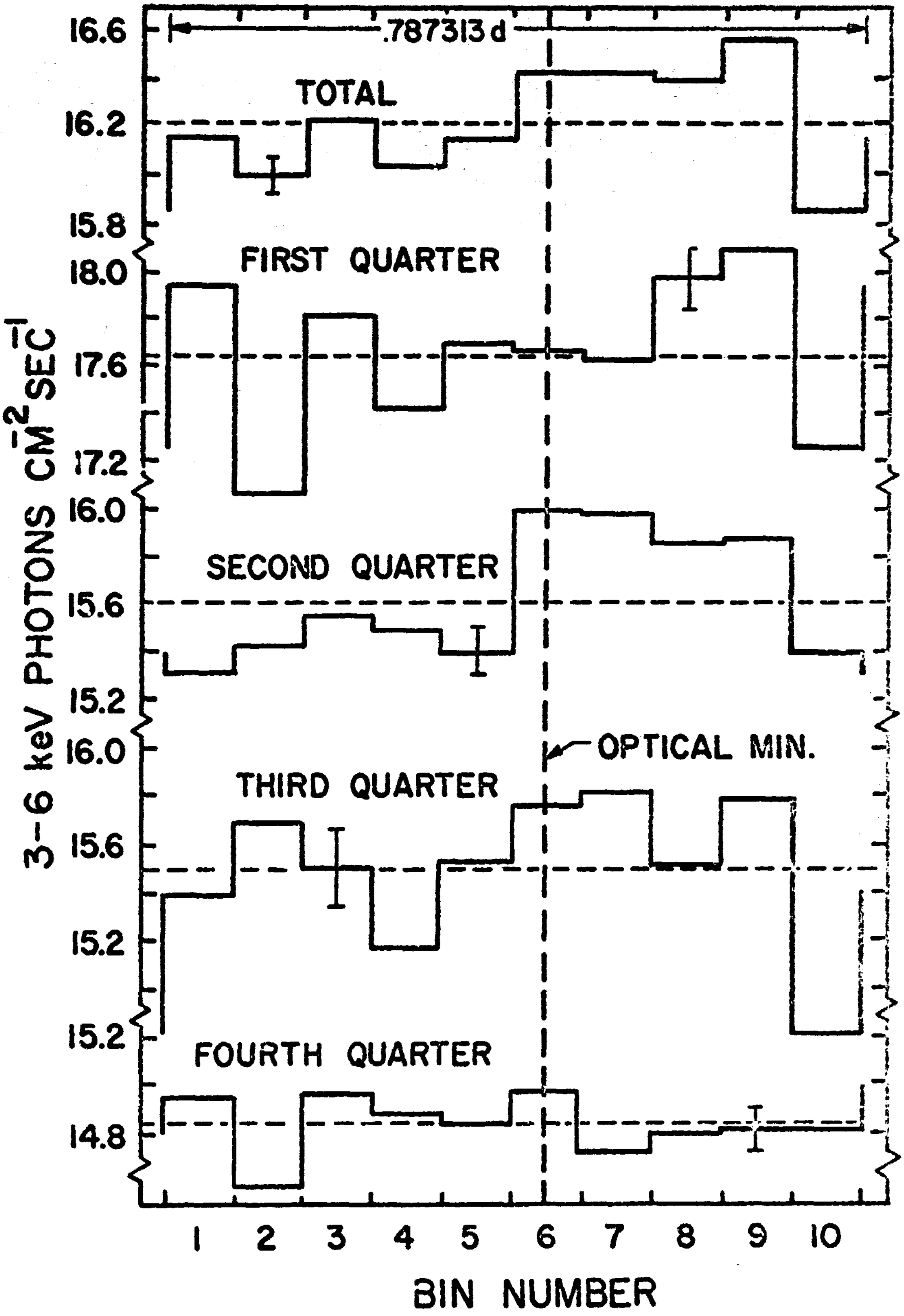

.787313 d
TOTAL
FIRST QUARTER
SECOND QUARTER
THIRD QUARTER
FOURTH QUARTER
OPTICAL MIN.
16.6
16.2
15.8
18.0
17.6
17.2
16.0
15.6
15.2
16.0
15.6
15.2
15.2
14.8
3–6 keV PHOTONS CM⁻² SEC⁻¹
1
2
3
4
5
6
7
8
9
10
BIN NUMBER

Fig. 1

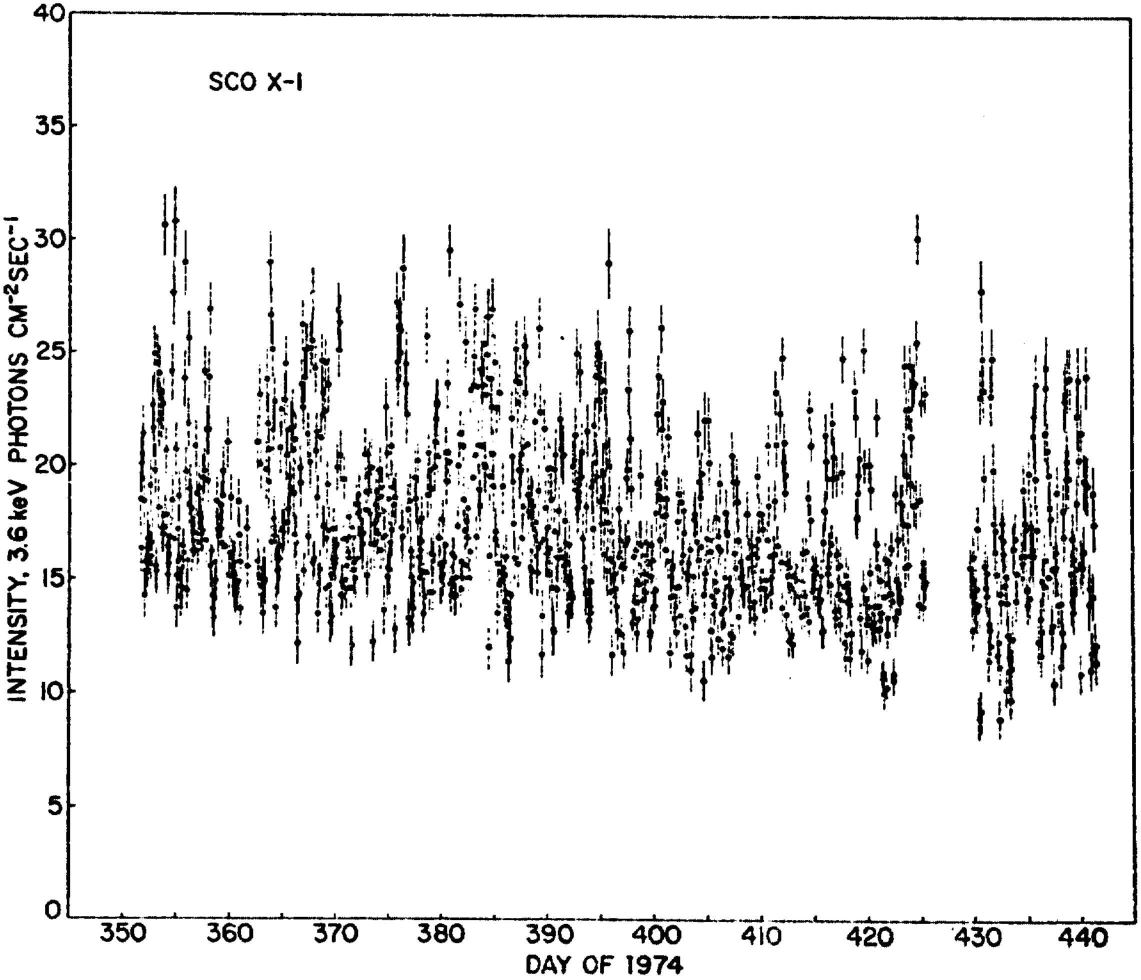

SCO X-1
INTENSITY, 3.6 keV PHOTONS CM^{-2}SEC^{-1}
40
35
30
25
20
15
10
5
0
350
360
370
380
390
400
410
420
430
440
DAY OF 1974

Fig. 2a

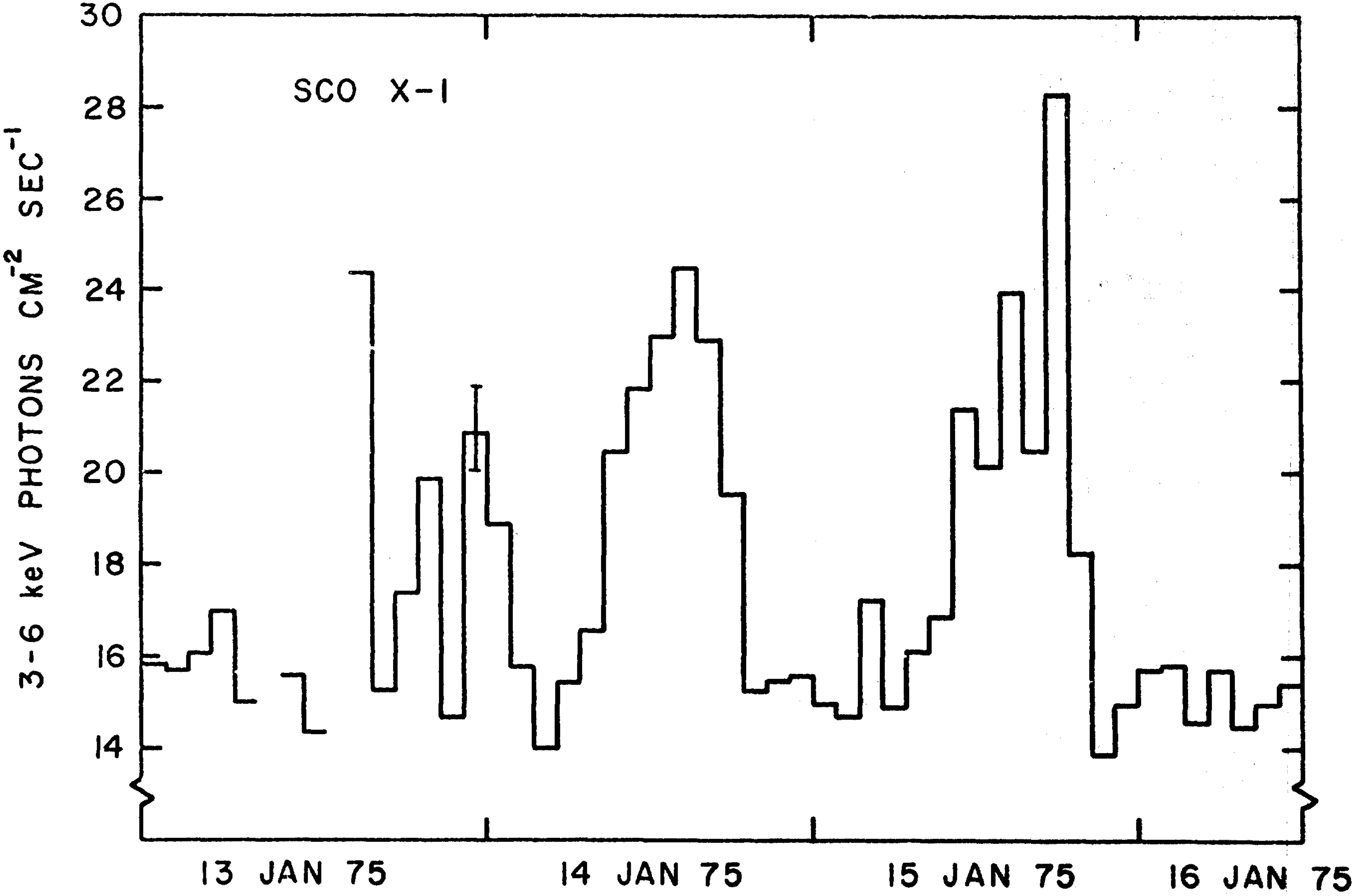
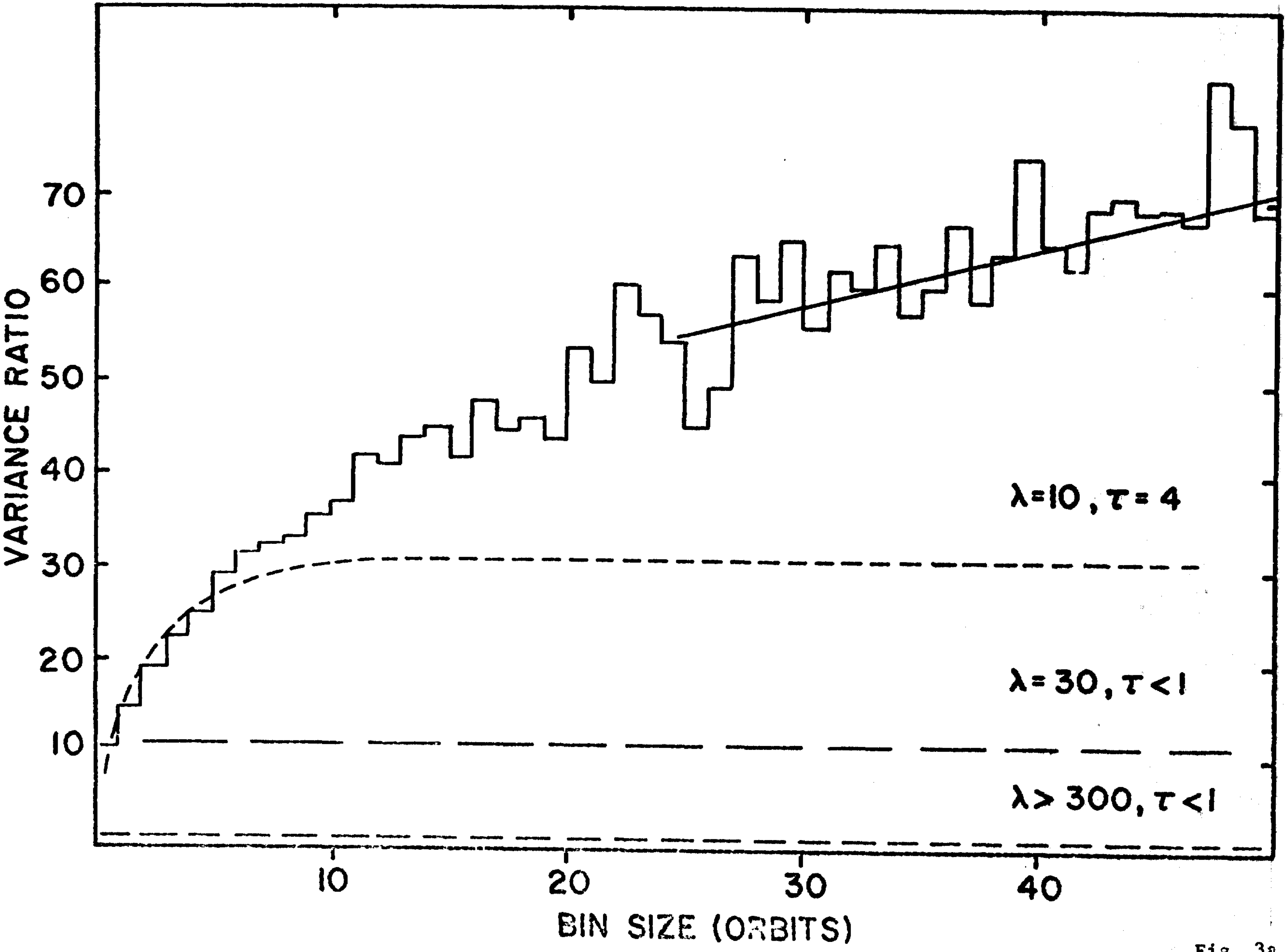

SCO X-1
3-6 keV PHOTONS CM^{-2} SEC^{-1}
30
28
26
24
22
20
18
16
14
13 JAN 75
14 JAN 75
15 JAN 75
16 JAN 75

Fig. 2b


VARIANCE RATIO
70
60
50
40
30
20
10
BIN SIZE (ORBITS)
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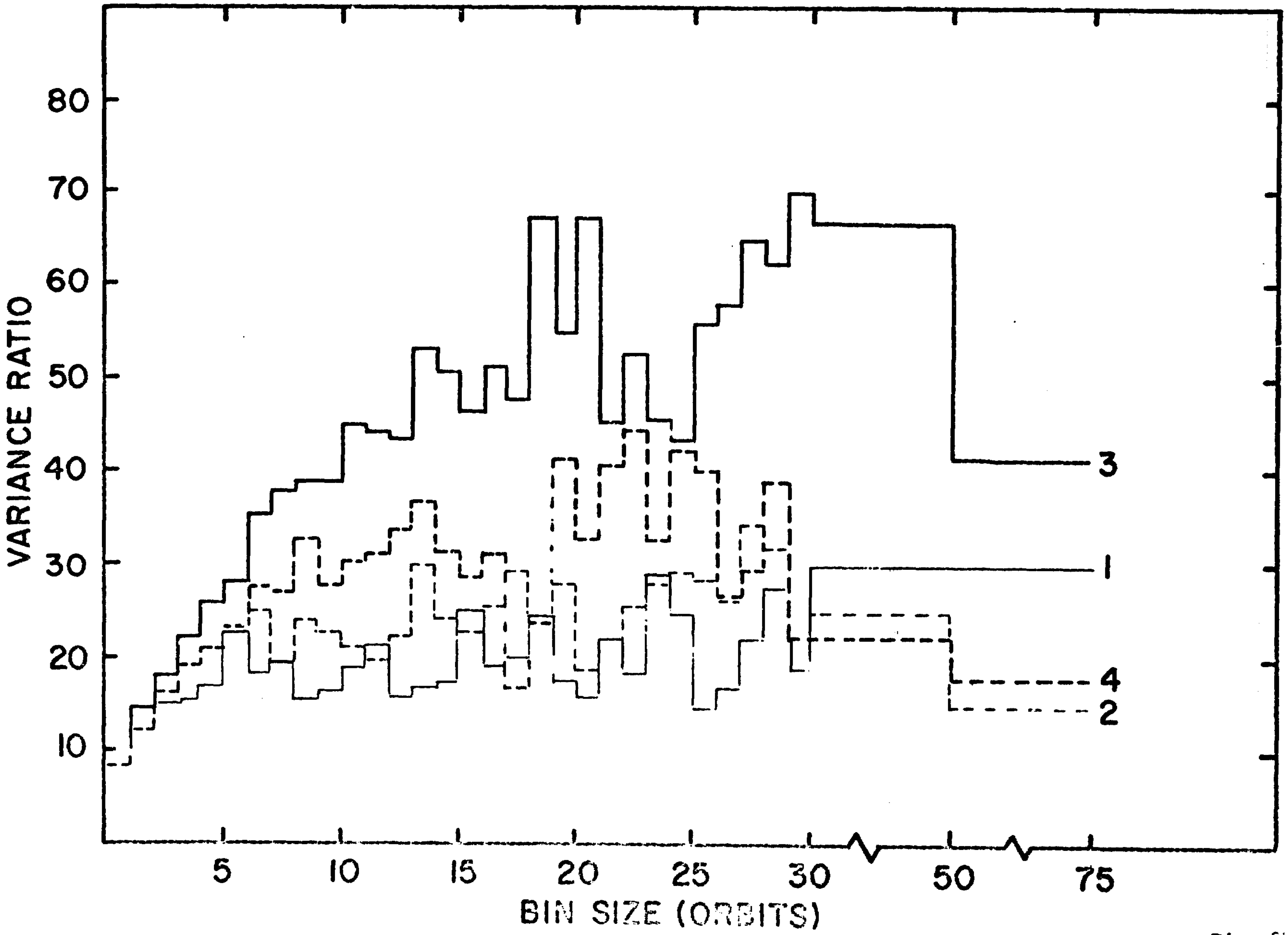
20
30
40
λ=10, τ=4
λ=30, τ<1
λ>300, τ<1

Fig. 3a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70
60
50
40
30
20
10
5
10
15
20
25
30
50
75
BIN SIZE (ORBITS)
3
1
4
2

Fig. 3b