FINAL REPORT

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TITLE OF RESEARCH:

Detailed Studies of the Nonperiodic Time Variability of Several Galactic X-Ray Sources

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DESCRIPTION OF RESEARCH

Our study of the time variability of the galactic X-ray sources which exhibit nonperiodic intensity fluctuations has concentrated on the source Cygnus X-1. The data which we have examined were obtained with the wide field-of-view collimator aboard the *Uhuru* satellite. Our research program, however, has had three principal goals: first of all, to develop the computer software and expertise to perform analyses of the time variability of the galactic X-ray sources; second, the specific application of these programs to the study of the source Cygnus X-1 in order to obtain a further insight to the emission mechanism of this source; and finally, to develop a better understanding of what may be learned from further studies along the same lines. We feel that we have succeeded in all three endeavors.

I. Software Development

Computer software has been written to accomplish the following:

(a) To detrend the *Uhuru* data; i.e., to remove the angular response of the collimator from the raw data. These programs are, in fact, applicable to data received by any scanning receiver.

(b) To calculate autocorrelation functions. Autocorrelation functions are calculated for the detrended data for each independent observation of an X-ray source. The energy bandwidth can be selected.

(c) To calculate a cross-correlation function. The data in two operator-selected energy bandwidths are cross correlated for each observation of an X-ray source.

(d) To perform Fourier analysis. The autocorrelation functions can be multiplied by a variety of standard spectral windows (Bartlett, Parzen, and Tukey), and a power density spectrum is computed.

(e) To provide averages. Software to determine the average overall independent observations of the source for any of the above functions.

(f) To perform long-term time variability analyses. This software is used to calculate the unsmoothed, sample power spectrum of the long-term (days) variations of any chosen parameter such as the mean intensity per observation, the cross-correlation at zero time delay, etc.

(g) To simulate with Monte Carlo techniques sources exhibiting different categories of time variability and to produce probability distributions of parameters derived from the raw data. One of the most important aspects of data analysis lies in the understanding of the statistical uncertainties produced by chance fluctuations in the experimental data. This is particularly complicated in the analysis of the nonperiodic fluctuating X-ray sources where one is faced with two categories of signal fluctuations, viz., that due to the source itself and that due to photon statistics. Clearly errors in derived quantities are not simply found by the propagation of the estimated uncertainty of the latter. Furthermore, we are dealing with a situation where the probability density function governing the source variability is not known *a priori*. It has been extremely useful for us to simulate the results of experiments assuming a particular source variability such as white-noise and shot-noise sources. In addition to allowing us to derive probability distributions, this software was used to check the analysis routines for those cases where the results are well understood, e.g., the autocorrelation function for a DC source with counting statistics should be (on the average) zero for all time delays other than zero and should exhibit fluctuations with variance 1/N where N is the total number of time delays. Finally, this software allowed us to study the impact on our results of possible systematic effects such as, for example, the assumption that the angular response of the collimator was nontriangular, etc.

II. Cygnus X-1 Results

A. Short-Term Time Variability

Seventy-one independent observations of the X-ray source Cygnus X-1, obtained with the wide field-of-view proportional counter aboard the *Uhuru* satellite were examined. A detailed discussion of our analysis of the short-term (<15 sec) variability is contained in a paper, "Short-Term Time Variability of Cygnus X-1," which has been accepted for publication in the *Astrophysical Journal (Letters)*. A preprint is included as Appendix I to this report.

Figure 1a in the Appendix shows the X-ray intensity as a function of time for a typical observation. All the data were obtained with time resolution of 0.192 sec and the energy bandwidth of observation selected by us for analysis was from 2.1 to 16.4 keV. Briefly, our results are as follows: (1) The time averaged autocorrelation function and its corresponding power density spectrum (the latter, apart from the effects of smoothing, is the Fourier transform of the former) are clearly not consistent with a steady (DC), white noise, nor periodically pulsed source. (2) Furthermore, the shape of the autocorrelation function, essentially a simple exponential with e folding time of 0.45 sec is a classic example of that which would be produced by a randomly pulsed or "shot-noise" source. This apparent behavior would be a natural consequence of the formation of local "hot" spots in an accretion disk, which most theoretical models of this source invoke. (3) We find *no* evidence for any energy dependence in the autocorrelation function or power-density spectrum. In fact, we have discovered a serious error in the interpretation of previous results by other workers in this field which led them to present, incorrectly, evidence for an energy dependent effect. (4) We find a 100% correlation in time on the scales of the order of 0.2 sec between flux in different energy bandwidths. This result would indicate that the hot spots or flares that give rise to low- and high-energy photons are identical and have the same spectrum. (5) When we compare our results with other similar analyses obtained since the spectral transition of 1971 March, once the error discussed in our paper is taken into account, we find that the results are in agreement and would therefore indicate that there is a *steady* feature of this source, namely, the mean rate of occurrence of flares and the mean cooling time. These results are consistent with the qualitative features of most of the standard accretion-disk models which invoke X-ray emission from two distinct regions: an optically thin, inner region from which the high-energy flux emanates, and an optically thick, outer region from which the lower-energy flux is emitted. The X-ray flux in the 2–16-keV range that we have examined is clearly from a single region as the 100% cross-correlation indicates. This result is consistent with the hypothesis that during the spectral transition the relative intensities from the two regions shifted dramatically. The similarity between the posttransition spectrum and the high-energy component of the pretransition spectrum would further indicate that we are observing the flux from the inner region. The cooling time that we detect can then be used to estimate the electron density of the emission volume. We wish to point out that if the hypothesis of two distinct emission regions is correct, then we would *not* expect to observe a 100% cross correlation between the low- and high-energy components of the pretransition data. We discuss this point in more detail in a proposal for continuation of support being submitted under separate cover.

B. Long-Term Time Variability

In addition to examining the short-term time variations of Cygnus X-1, we have also examined the long-term (~days) time variations of several parameters over the 12 days spanned by the 71 observations. Of especial interest, of course, are variations occurring at the 5.6-day period detected from the optical counterpart. Unfortunately, the limited data span of 12 days and the poor quality of the *Uhuru* observations (in the sense that counting statistics dominate each individual observation) make it difficult to draw any definite conclusions. Nevertheless we have proceeded to examine the long-term time variations of the following variables.

(1) The Background.

The sample spectrum of the background for each observation is shown in Figure 1. This spectrum is perfectly consistent with white noise and indicated to us that, despite the nonuniform data sampling, we were not subject to gross systematic effects in the resulting power spectrum. This conclusion was also confirmed using the Monte Carlo simulations with white-noise sources.

(2) The Mean Count Rate per Observation

The mean count rate per observation for these observations, corrected for the spacecraft attitude, is shown in Figure 2.

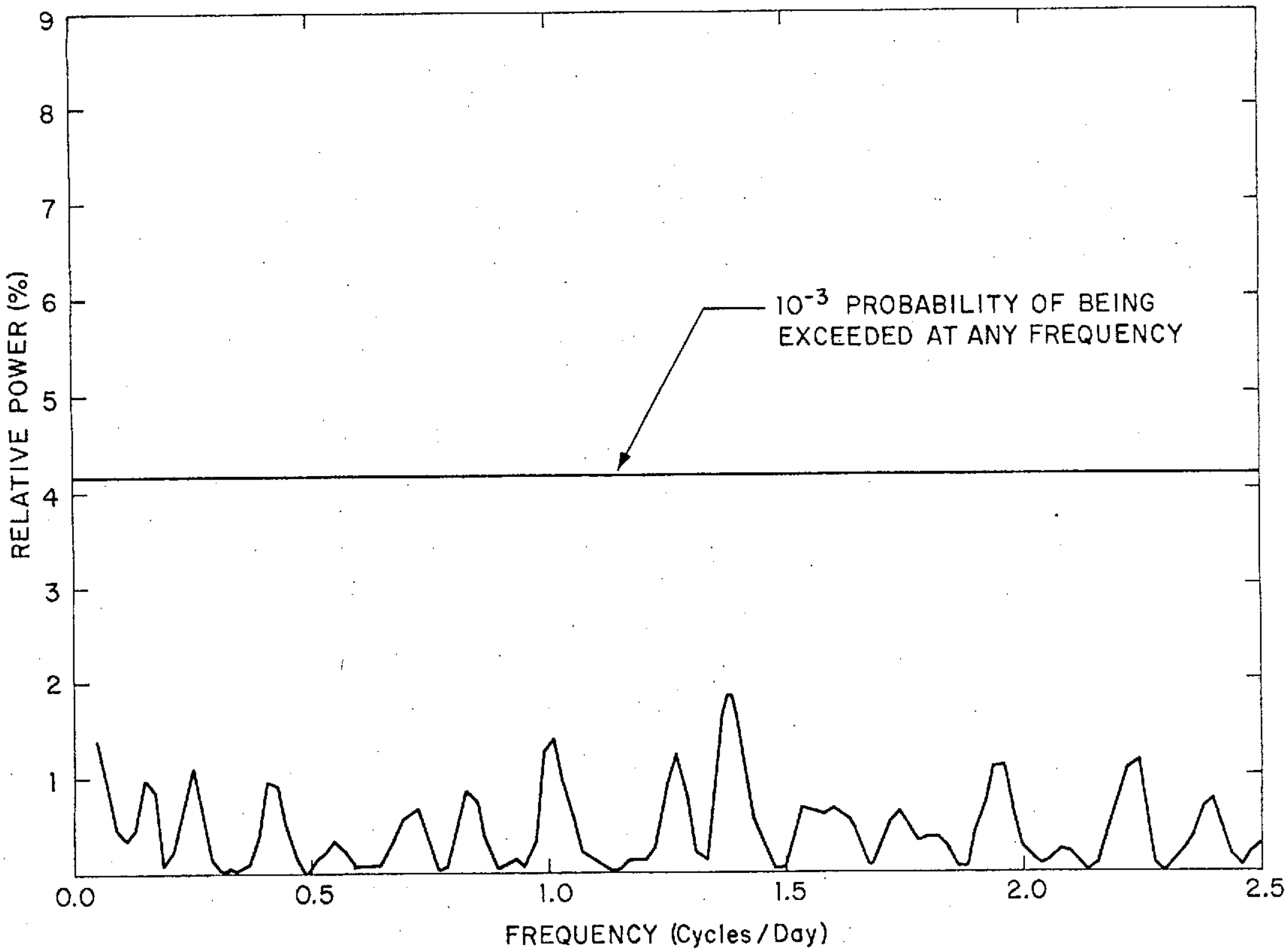

FIG. 1. — Power spectrum of the background for 71 observations of Cygnus X-1 in the time interval from 9 to 22 January 1972.

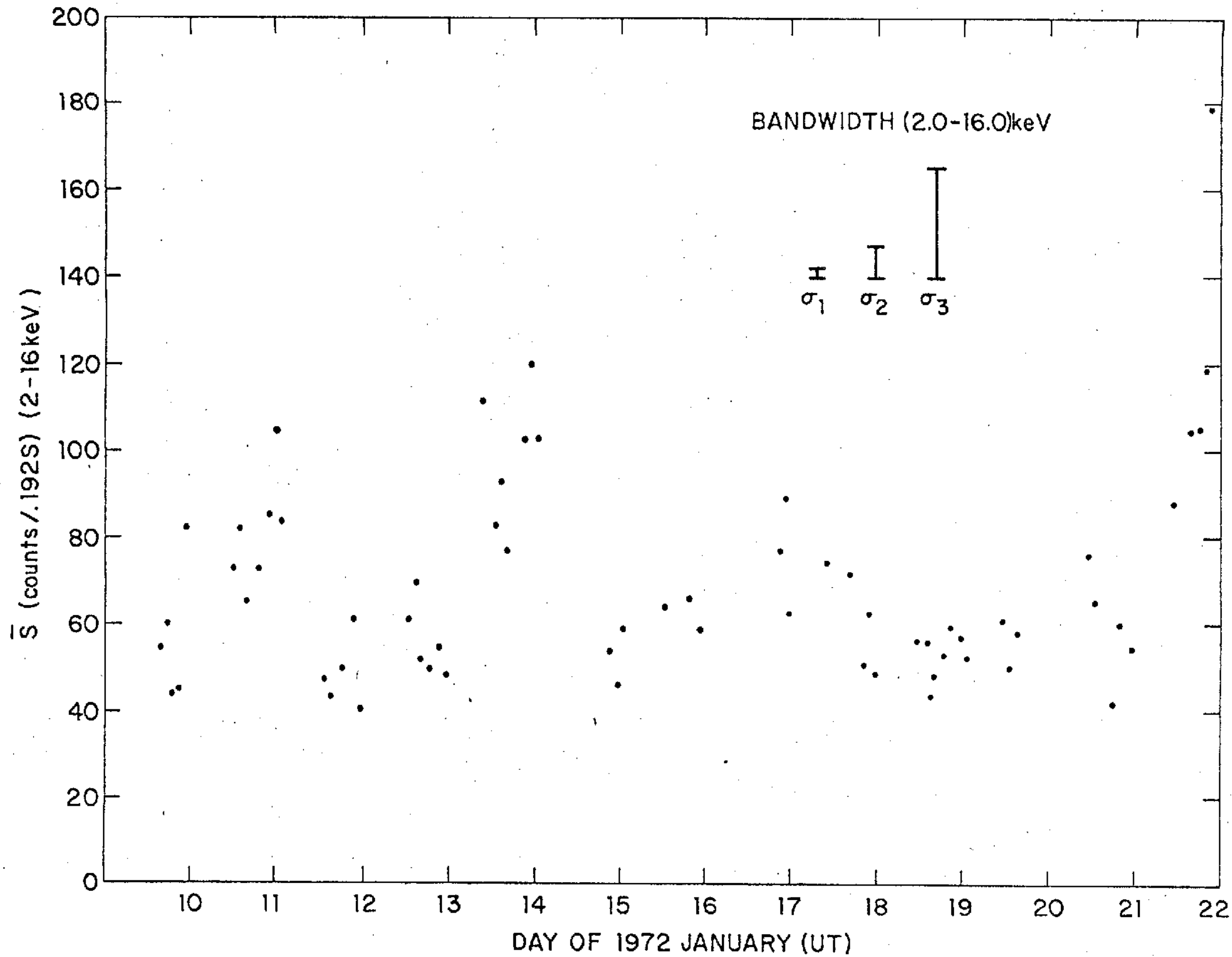

FIG. 2. — Intensity of Cygnus X-1 as a function of time.

Even in this rather limited data set we see variations in flux by as much as a factor of 4. The three error bars shown in the figure represent, respectively, the typical statistical uncertainty based on the flux variations in each observation (σ_1), the typical uncertainty in the intensity resulting from the uncertainty in the aspect correction (σ_2), and finally, the uncertainty based on the scatter of the data about the mean (σ_3). The fact that the latter is almost three times larger than the former two indicates of course that these intensity variations are not consistent with those expected from a DC source with counting statistics. This can be seen more clearly from the resulting power spectrum in Figure 3 where there are three peaks, each of probability of chance occurrence of 5×10^{-3} or less. In fact, these results make extremely unlikely that the long-term variations follow a white-noise process (with variance ${\sigma_3}^2$) as the probability of obtaining such peaks by chance is inordinately small. We are then faced with the following possible conclusions: (a) the long-term variations are consistent with those due to a white-noise source, and we happened to have observed the highly improbable chance occurrence of three statistically significant peaks in the power spectrum, or (b) in general, the source is a white-noise source and two or even all three of the peaks in the power spectrum are indicative of a periodic process. Unfortunately, we have *no a priori* reason for singling out any of the periods of 3.6, 2.8, and 1.6 days for any special significance. We do find it interesting, however, that the 2.8-day variation, shown superimposed on the data in Figure 4, is *in phase* with the 2.8-day variations observed in the intermediate band b-magnitude of the visible companion HDE 226868 (as reported, e.g., by Lester *et al.*, Nature Phys. Sci. 241, 125 [1973]).

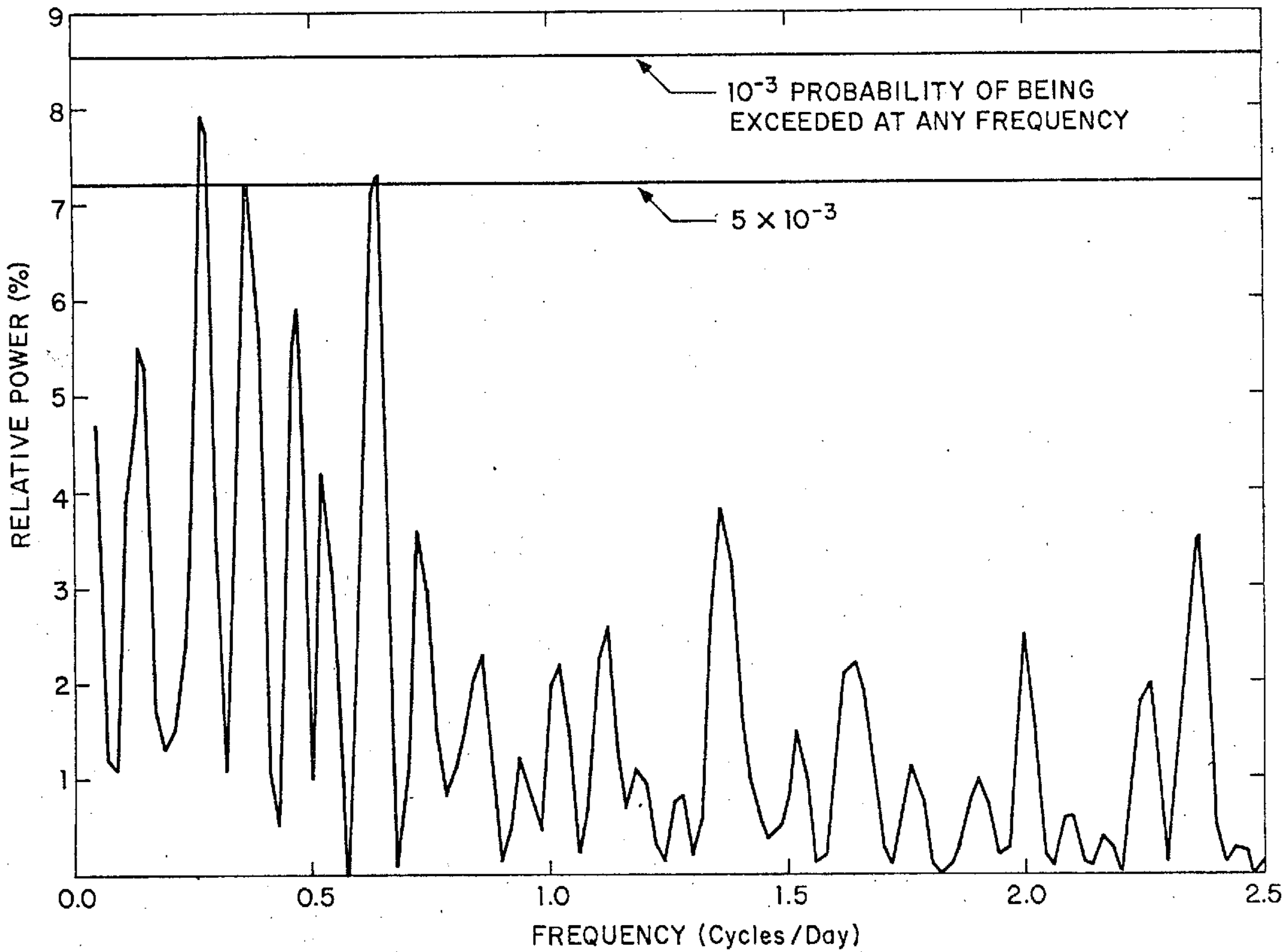

FIG. 3. — Power spectrum of the mean count rate.

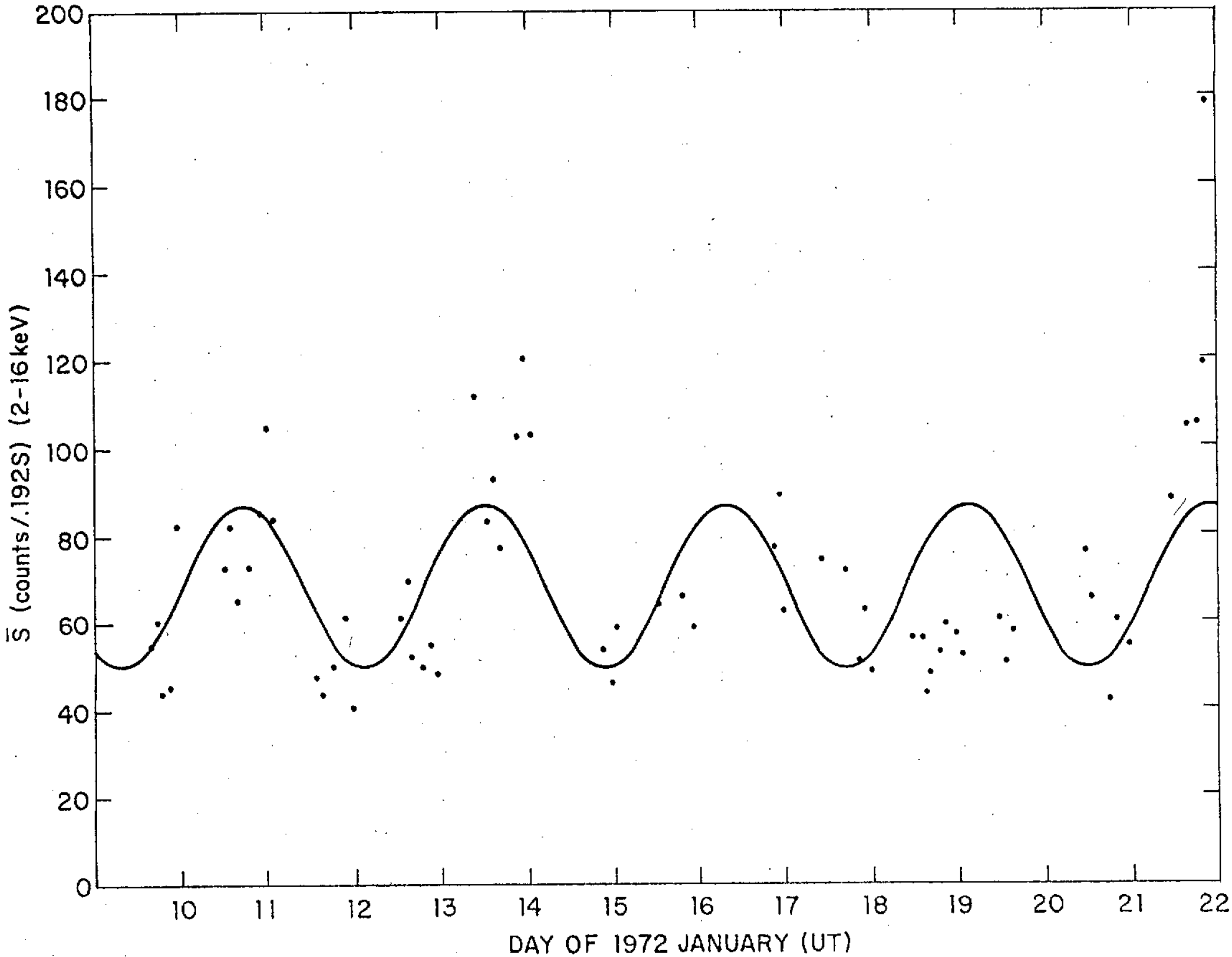

FIG. 4. — Intensity as a function of time. The 2.8-day variability is shown as a solid line.

(c) The most reasonable interpretation, however, is that the long-term variations are describable by some unidentified stochastic process. In fact, one could speculate about a "superflare" process as the high power at low frequencies could indicate.

We should note that it is quite possible that the uncertainties in the aspect correction are significantly underestimated. These data were obtained after the *Uhuru* star sensor became inoperative, and spacecraft aspect was obtained by comparing the intensity between back-to-back observation of the two detectors with differing fields of view. The short-term shot-noise variations of the source, though small compared with the errors produced by counting statistics, were not taken into account in the aspect corrections sent to us by the group at the Smithsonian Astrophysical Observatory.

(3) The Shot Parameters

Clearly a very interesting set of variables is the rate of occurrence of the shots (λ) and their decay time τ. Unfortunately, the signal-to-noise ratio of the *Uhuru* observations is quite poor so that it is effectively impossible to make a meaningful measurement of these quantities for a single observation of the source. Thus we are forced to lump observations together which, of course, implies a reduced sensitivity to long-term variations.

The resulting mean shot-model parameters as a function of phase for four phases are shown in Figure 5. There is clearly a correlation between the value of the parameters and binary phase outside the statistical variations, but there are not enough data to warrant an unambiguous selection of this period other than on *a priori* grounds.

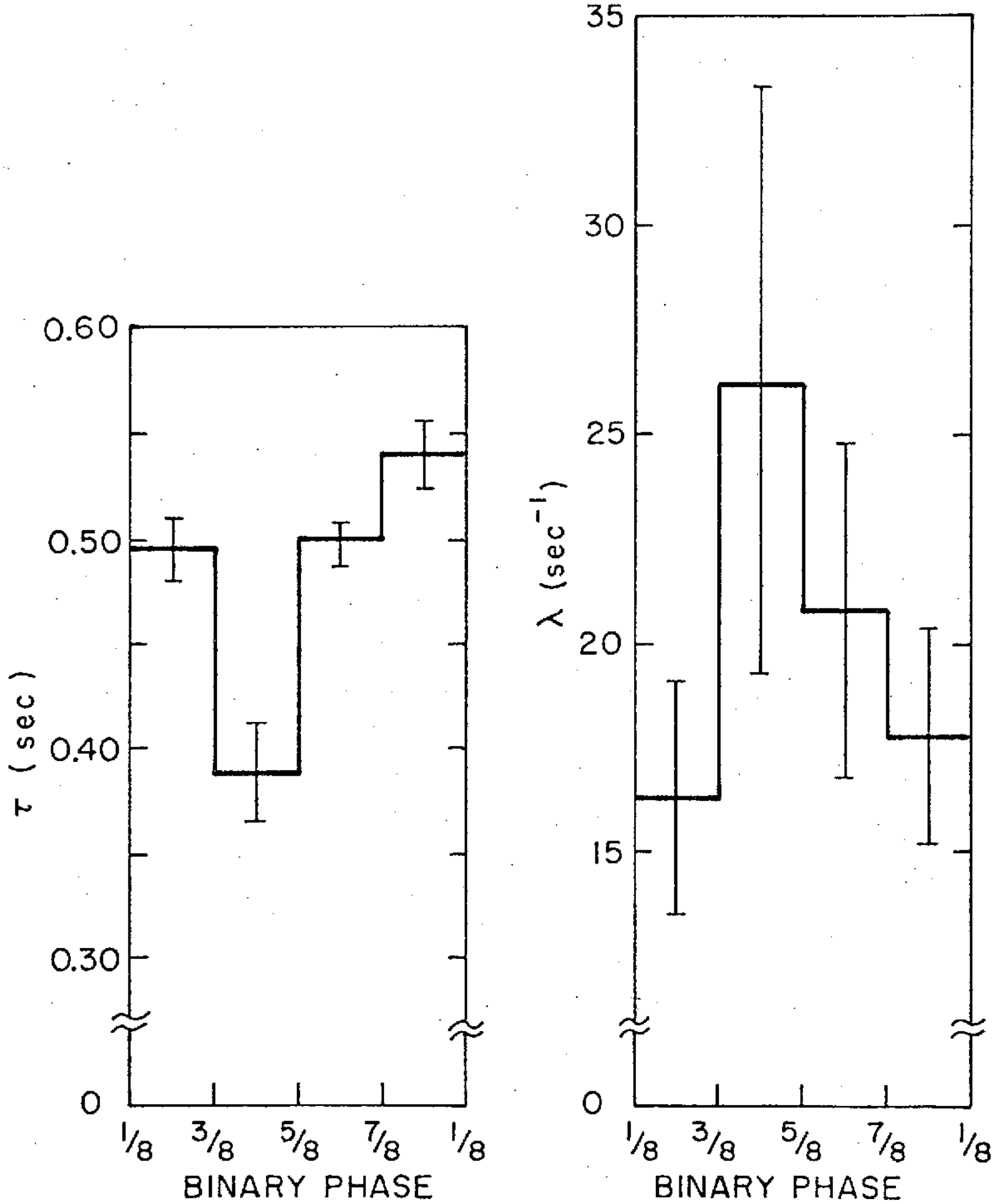

FIG. 5. — The shot decay (flare cooling) time and shot (flare) rate as a function of binary phase for an assumed 5-6 day period.

III. Summary and Conclusions

We have prepared and tested computer software necessary for the analysis of the time variability of X-ray sources. We have examined in detail 71 *Uhuru* observations of the black-hole candidate Cygnus X-1. We have shown that the X-ray emission can be best represented as arising from randomly occurring X-ray flares with a mean rate of occurrence of 18 flares sec^{-1} and a mean cooling time of approximately 1/2 sec. Furthermore the data show that photons in the 2—16-keV bandwidth arise from within the same flares. Finally, we have found evidence that the mean flare rate and cooling time have been constant since the source underwent a spectral transition in 1971 March.

We have examined the long-term variations of several parameters associated with the X-ray emission from this object with the basic result that further detailed investigations are necessary.

PUBLICATIONS

M. C. Weisskopf, S. M. Kahn, and P. G. Sutherland, "Short-Term Time Variability of Cygnus X-1," to be published in Astrophys. J. (Letters).

PAPERS PRESENTED AT SCIENTIFIC MEETINGS

M. C. Weisskopf, P. G. Sutherland, and S. Kahn, "Analysis of the Time Variability of Cygnus X-1," at 144th meeting of the American Astronomical Society, University of Florida, Gainesville, Florida, 10-13 December 1974; Bull. Am. Astron. Soc. 6, 445 (1974).

M. C. Weisskopf, S. M. Kahn, and P. G. Sutherland, "Short-Term Time Variability of Cygnus X-1," at American Physical Society meeting, Washington, D. C., 28 April-1 May 1975, Paper DI 5, Bull. Am. Phys. Soc. II, 20, 603 (1975).

S. M. Kahn, "Short-Term Time Variability of Cygnus X-1," at 29th Annual Eastern Colleges Scientific Conference, Widener College, Chester, Pennsylvania, April 4, 1975.

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APPENDIX I

SHORT-TERM TIME VARIABILITY OF CYGNUS X-1

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ABSTRACT

Autocorrelation functions, power density spectra, and cross-correlation functions were calculated for 71 observations of Cyg X-1 obtained by the *Uhuru* satellite. The average autocorrelation function and power density spectrum were found to be independent of energy and consistent with a shot-noise source with a characteristic time constant of 0.45 s. The data in different energy bands were found to be 100 percent correlated.

Subject headings:

I. OBSERVATIONS AND DETRENDING

In this *Letter* we present the results of a study of the short-term time variability of the source Cyg X-1. The data were obtained with the wide field of view ($5^\circ.1$) proportional counter aboard the *Uhuru* satellite (Giacconi *et al.* 1971). Figure 1a shows the X-ray intensity as a function of time for data obtained in the energy bandwidth of 2.1 to 16.4 keV from a single observation of the source on 1972 January 9.

In order to remove the angular response of the detector, the data were examined visually to determine when the source was in or out of the field of view. The off-source data were then averaged to determine the background level for the observation. After subtracting background, the on-source data were fit by means of a (weighted) least-squares technique to a triangular response function with the width, height, and center of the triangle left as free parameters. The weighting factors were based on the errors in each data point due to counting statistics, including the effects of background subtraction. The detrending process was completed by subsequently dividing the source data by the (normalized) best-fit, triangular response function. The error in each data point attributed to counting statistics was propagated through this procedure. The detrended data for the 1972 January 9 observation are shown in figure 1b. As indicated in the figure, only that portion of the detrended data for which the propagated counting statistics error is within a factor of two of the minimum value was then selected for further analysis.

Seventy-one observations of Cyg X-1 obtained by the *Uhuru* satellite in the time interval from 1972 January 9–27 were detrended in the manner described above.

II. THE AUTOCORRELATION-FUNCTION ANALYSIS

In order to characterize the short-term time variability of the source, an autocorrelation function (ACF) $\rho(u)$ was calculated for each observation where

$$\rho(u) \equiv r(u)/r(o) \tag{1}$$

and

$$r(u) = \frac{\sum_{i=1}^{N-u} \frac{(S_i - \bar{S})}{\sigma_i} \frac{(S_{i+u} - \bar{S})}{\sigma_{i+u}}}{\sum_{i=1}^{N} 1/\sigma_i^2} . \tag{2}$$

Here S_i and σ_i are the (detrended) counting rate and corresponding error in the i^{th} time bin, and

$$\bar{S} = \frac{\sum_{i=1}^{N} S_i/\sigma_i^{2}}{\sum_{i=1}^{N} 1/\sigma_i^{2}} \tag{3}$$

is the mean counting rate per 0.192-s bin.

The weighting factors σ_i were introduced into equations (2) and (3) to account for the systematic increase in the errors outwards from the center of the triangle.

The average ACF for the 71 observations and its corresponding power density spectrum* are shown as the dashed lines in figure 2. It is important to note that the functions shown as the dashed lines in figure 2 are *not* representative of the behavior of the source but are biased due to the effects of counting statistics.

More explicitly, the ACF defined in equation (1) is an estimate of the statistical function

$$\rho(\tau) = \frac{\langle z(t)\ z(t+\tau)\rangle}{V_z} \equiv \frac{\langle zz\rangle_\tau}{V_z} \quad , \tag{4}$$

where the stochastic variable z is the detected counting rate with total

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*The power density is defined as

$$P(f) = 2\Delta[1 + 2 \sum_{k=1}^{L-1} \rho(k)\ w(k) \cos 2\pi f(k)] \quad ,$$

where $0 \leq f \leq (2\Delta)^{-1}$, Δ is the sampling time interval (0.192 s), and w(k) is a smoothing function. We note that P(f) summed over all (N) independent, positive frequencies is $N\Delta$.

variance V_z and the average indicated by the brackets is performed over an ensemble of observations (see, for example, Jenkins and Watts 1968). If the signal z(t) is stationary (in the statistical sense), then ρ is only a function of τ, as indicated, and may be estimated through equation (1). Due to the discrete nature of the photon signal, we can write $z = x + y$ with x the "true" source signal and y representing the effects of counting statistics. Then we have

$$\rho(\tau) = \frac{\langle zz \rangle_\tau}{V_z} = \frac{\langle xx \rangle_\tau + \langle xy + yx \rangle_\tau + \langle yy \rangle_\tau}{V_z} \quad . \tag{5}$$

As the counting statistics are uncorrelated with the source, then in the ensemble average the cross terms vanish, and $V_z = V_x + V_y$. Since y is effectively a white noise signal, $\langle yy \rangle_0 = V_y$ but $\langle yy \rangle_\tau = 0$ for all $\tau \neq 0$, and thus

$$\rho(\tau) = \begin{cases} 1 & \tau = 0 \\ \dfrac{\langle xx \rangle_\tau}{V_z} = \dfrac{V_x}{V_z}\,\rho_x(\tau) & \tau \neq 0 \end{cases} , \tag{6}$$

with $\rho_x(\tau)$ the ACF of the source.

Equation (6) clearly shows that the measured ACF will be biased by the ratio of the source variance to the total variance. *Only* in the limit where the total and source variances are identical, i.e., when the fluctuations in the data produced by counting statistics are negligible, will the ACF defined in equation (1) represent the true time variability of the source. This point seems to have been overlooked in a previous analysis of six *Uhuru* observations of Cyg X-1 by Brinkman *et al.* (1974) and led to erroneous conclusions as discussed below.

The procedure that we adopted to determine the ACF representative of the behavior of the source is as follows: The total variance for each observation is given by r(o) (see eq. [1]), and the contribution to the total variance due to counting statistics was estimated to be

$$V_y = N / \left(\sum_{i=1}^{N} 1/\sigma_i^2 \right) \quad . \tag{7}$$

The source variance is then given by $V_x = V - V_y$. We then averaged the 71 ACF's and corrected for the effects of counting statistics by multiplying $\bar{\rho}(\tau \neq 0)$ by $\bar{V}_z(\bar{V}_x)^{-1}$ where $\bar{V}_z$ and $\bar{V}_x$ are the total and source variances averaged over the 71 observations. We have tested this approach by means of Monte Carlo shot-noise simulations of the experimental data, and we find that by this technique we are able: a) to estimate the source variance to better than 20 percent and b) to reconstruct the correct ACF with similar accuracy. The correction factor for the experimental data is 1.6. The corrected ACF and corresponding power density spectrum are shown as the solid lines in figure 2. The error bars are *not* based on counting statistics but rather are computed from the scatter about the mean of the appropriate variable for each observation. The increased errors in the corrected functions follow from the uncertainties in the average variances.

A. Discussion

The ACF shown in figure 2 falls exponentially to zero with an e-folding time of 0.45 s and clearly confirms the now well-established result that the short-term time variations of Cyg X-1 are consistent with neither a steady, a white noise, nor a pulsed source.

Power density spectra were determined by smoothing the ACF with a Tukey window $w(k) = 0.5[1 + \cos(\pi k/L)]$, where L specifies the truncation point. We have also computed power density spectra utilizing Bartlett and Parzen windows and find no significant differences among the results. The power density spectrum shown in figure 2 was determined with $L = 24$, which seemed to realize a reasonable compromise between bandwidth and variance for these data.

The "peak" in the power spectrum at low frequencies should be interpreted only as an indication of high power at low frequencies and not an indication of the presence of a pulsed component. The slight turnover near zero frequency is a result of the fact that $P(o) \simeq 0$ and that with $L = 24$ we are averaging over only a few frequencies. As the truncation point L is reduced, the turnover disappears as expected.

As was first pointed out by Terrell (1972), ACF's and power spectra of the type shown in figure 2 are examples of those which would be produced by a randomly pulsed or "shot noise" source. This apparent behavior would be a natural consequence of the formation of local "hot" spots (flares) in an accretion disk (see for examples Thorne and Price 1975) which have a lifetime of the order of a second. Regardless of the physical interpretation, a shot process can be used to summarize the results. The data that we have examined are best represented by an exponential shot model with characteristic time of 0.45 s and a shot rate of 18 shots s^{-1}.

B. Energy Dependence

We have also examined the average ACF as a function of energy. In particular, we have compared the ACF for data in the 2.1 to 5.2 keV band with that for data in the 5.2 to 16.4 keV band. The measured ACF, equation (1), leads to the results reported by Brinkman *et al.* (1974), namely, that the high-energy ACF falls more rapidly to zero than that of the low-energy data. However, as different amounts of flux were detected in the two bandwidths, one might well expect the ratio $\bar{V}_z/\bar{V}_x$ to be different. In this case, conclusions drawn from the measured ACF's may be invalid. For the data that we have analyzed, the detected high-energy intensity was 37 percent of the low-energy flux, and the ACF correction factor $\bar{V}_z/\bar{V}_x$ was 2.8 for the high-energy data as compared to 2.0 for the low. Once the corrections to the ACF's are applied as shown in figure 3, we find no evidence for any energy dependence, and the results are identical with those shown in figure 2. Considering the strong similarity between our uncorrected results and those of Brinkman *et al.*, the fact that the data were taken with the same instrument, and the fewer number of observations, which would lead to greater uncertainty in the correction factors, we suspect that the latter experiment is consistent with no energy dependence.

III. CROSS-CORRELATION ANALYSIS

The cross correlation between the counting rate S_L in the low-energy band (2.1–5.2 keV) and the counting rate S_H in the high-energy band (5.2–16.4 keV) was also examined. For each observation of Cyg X-1 the cross correlation function (CCF)

$$CC(u) = \frac{\displaystyle\sum_{i=1}^{N-u} \left\{\frac{(S_{L,i} - \bar{S}_L)(S_{H,i+u} - \bar{S}_H)}{\sigma_{L,i}\,\sigma_{H,i+u}}\right\}}{[r_L(o)\ r_H(o)]^{1/2} \displaystyle\sum_{i=1}^{N} \frac{1}{\sigma_{L,i}} \frac{1}{\sigma_{H,i}}} \qquad (8)$$

was calculated; this function is normalized to fall between -1 and +1. As before, the CCF will only represent the behavior of the source in the limit where the fluctuations due to counting statistics are negligible. By an argument analogous to that leading to equation (6) we find

$$CC(u) = \left(\frac{V_{L,x}\ V_{H,x}}{V_L\ V_H}\right)^{1/2} CC_x(u) \quad , \qquad (9)$$

where CC_x is the true CCF of the source with variances $V_{L,x}$ and $V_{H,x}$ in the low- and high-energy bands, and V_L and V_H are the detected total variances in these bands. In practice, we calculated an average CC(u) for the 71 observations and then corrected it by the square root of the ratio of the average variances to obtain $CC_x(u)$. This corrected CCF is shown in figure 4.

The results of the cross-correlation analysis shown in figure 4 indicate effectively a 100 percent correlation in time between the high- and low-energy data (at least on time scales $\gtrsim$ 0.2 s) with no indication of any asymmetry. That is, the high-energy events neither lead nor lag the low-energy events. The most natural interpretation of this result is that the underlying shots, hot spots, or flares that give rise to the high- and low-energy photons are identical and have essentially the same spectrum from flare to flare. (If the photons in these two bands arose from different regions of the source, or the spectrum of a hot spot was quite variable, then any significant cross correlation would be unlikely.) A further argument that the sources of the low- and high-energy photons are indeed identical is that the ACF and CCF are identical in shape.

IV. CONCLUSIONS

We have shown that for data obtained in the time interval 1972 January 9-27 the short-term time variability of the source Cyg X-1 can be represented by a shot-noise model with characteristic time constant of 0.45 s, that the time variability is independent of energy, and that the cross correlation between events in different energy bandwidths is as large as 100 percent for time scales ~0.2 s. These results are consistent with the production of all of the 2–16-keV X-rays in random flares (of lifetime ~0.45 s) in the accretion disk around the compact object. Finally, we have shown that data obtained in a previous observation of the source (Brinkman *et al.* 1974) in 1971 June are entirely consistent with these results, indicating possibly that the short-term time variability seems to be constant on time scales on the order of at least several months. This conclusion is further substantiated by a recent rocket observation of Cyg X-1 in 1973 October (Boldt *et al.* 1974).

We note that all of these observations were performed after the spectral transition of 1971 March. A comparison of the variability before and after the spectral transition may provide further insight into the emission mechanism of this object.

We express our appreciation to the Principal Investigator of the *Uhuru* Observatory, Dr. R. Giacconi, and to the National Aeronautics and Space Administration for making the data available to us. In this regard, we also thank Dr. D. Koch, at American Science & Engineering, Inc., and Drs. E. Schreier, M. Ulmer, C. Jones, and W. Forman, at the Smithsonian Astrophysical Observatory. This work was supported by NASA under grant NGR 33-008-194. This *Letter* is Columbia Astrophysics Laboratory Contribution No. 107.

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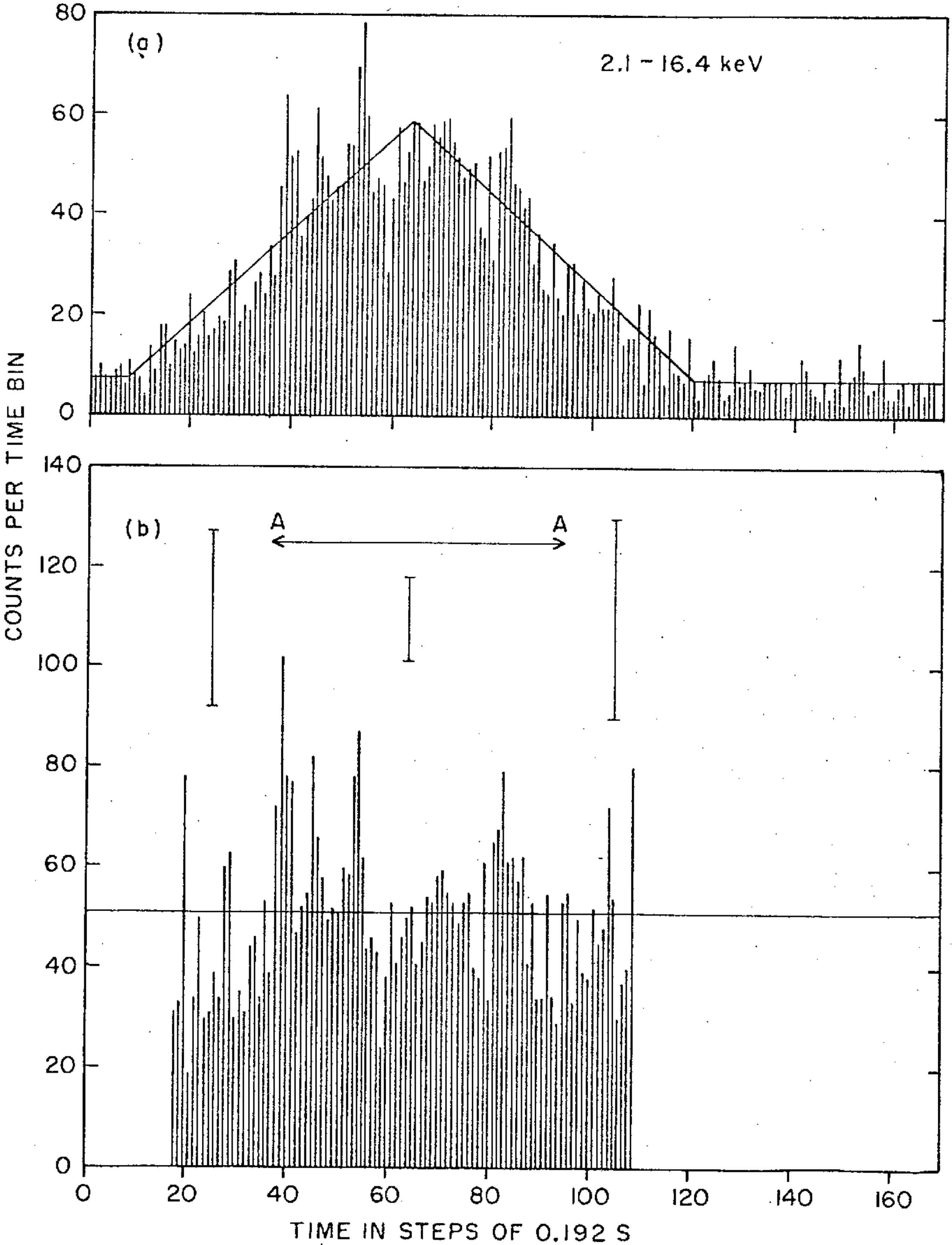
FIGURE CAPTIONS

FIG. 1. — a) Data obtained by the *Uhuru* satellite in a single observation of Cyg X-1 on 1972 January 9. b) The same data with the triangular response of the collimator removed. The error bars shown are based on counting statistics. The portion of the data indicated by A—A was selected for further analysis.

FIG. 2. — The average of 71 autocorrelation functions and power density spectra. Only the first 36 values of the autocorrelation function are shown. The error bars are based on the scatter of each data point about the mean for the results uncorrected for the bias produced by counting statistics. The error bars shown for the corrected functions also include the uncertainty in the correction factor.

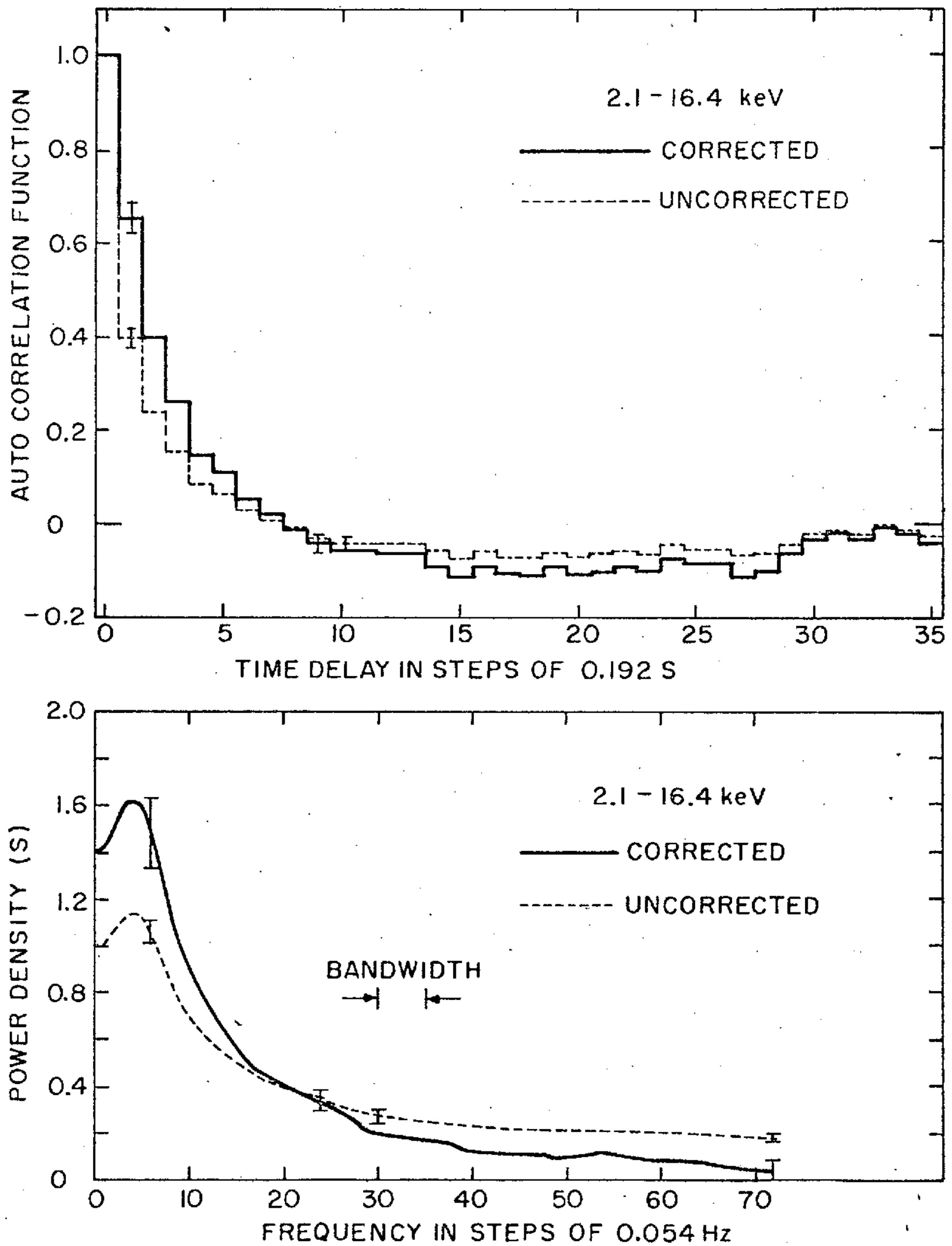
FIG. 3. — The corrected average autocorrelation functions for data in two energy bandwidths. Only the first 36 values of the autocorrelation functions are shown. The error bars shown are those for the high-energy data only. The error bars for the low-energy data are only slightly smaller. The error bars are based on the scatter of the individual data points about the mean and the uncertainty in the correction factor.

FIG. 4. — The average cross-correlation function corrected for bias produced by counting statistics. The error bars are based on the scatter of the individual data points about the mean and the uncertainty in the correction factor.



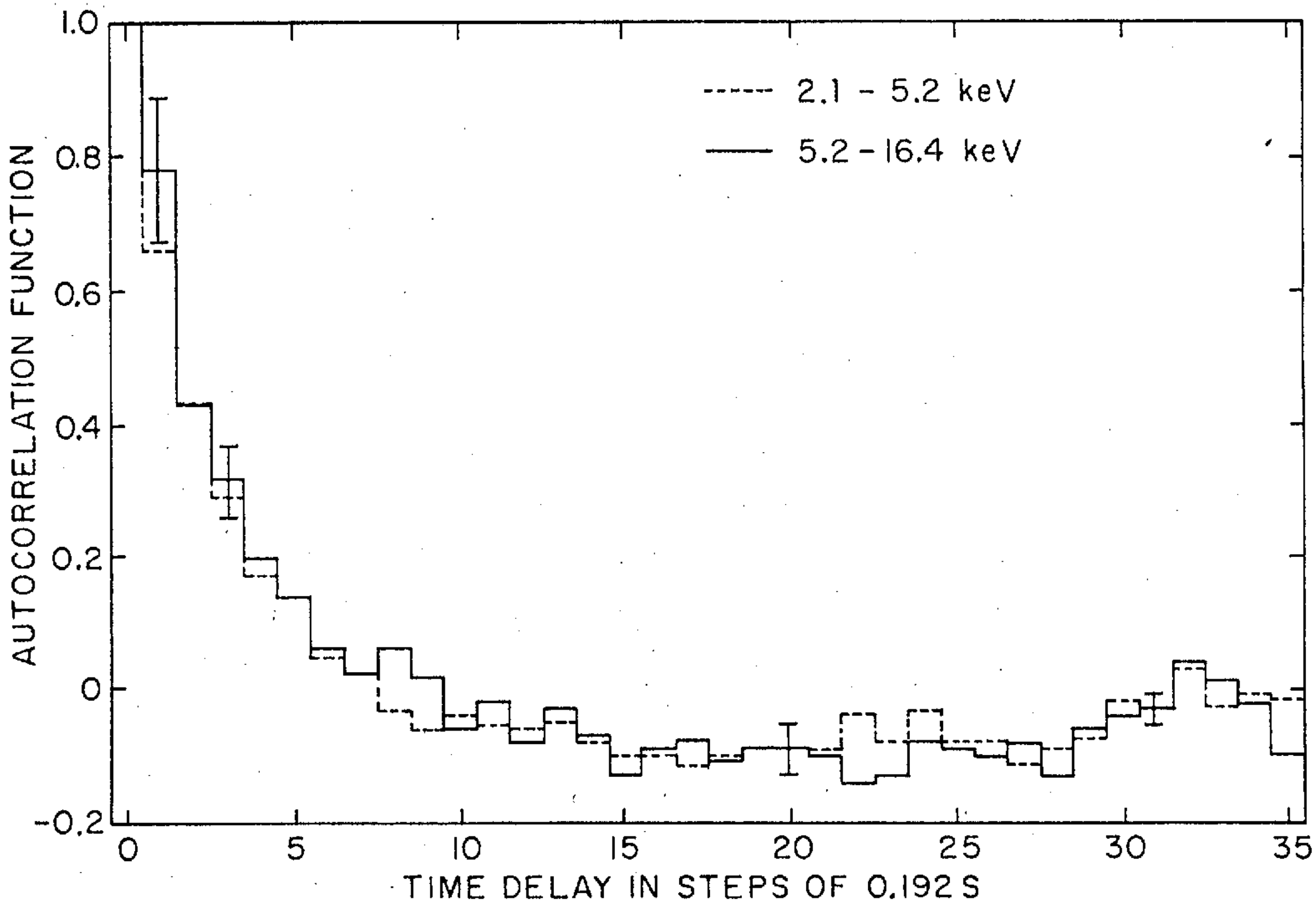
COUNTS PER TIME BIN
80
60
40
20
0
(a)
2.1 - 16.4 keV
140
120
100
80
60
40
20
0
(b)
A
A
0
20
40
60
80
100
120
140
160
TIME IN STEPS OF 0.192 S

FIG. 1



2.1 - 16.4 keV
CORRECTED
UNCORRECTED
AUTO CORRELATION FUNCTION
TIME DELAY IN STEPS OF 0.192 S
1.0
0.8
0.6
0.4
0.2
0
-0.2
0
5
10
15
20
25
30
35
2.1 - 16.4 keV
CORRECTED
UNCORRECTED
BANDWIDTH
POWER DENSITY (S)
FREQUENCY IN STEPS OF 0.054 Hz
2.0
1.6
1.2
0.8
0.4
0
0
10
20
30
40
50
60
70

FIG. 2



1.0
0.8
0.6
0.4
0.2
0
-0.2
AUTOCORRELATION FUNCTION
2.1 - 5.2 keV
5.2 - 16.4 keV
0
5
10
15
20
25
30
35
TIME DELAY IN STEPS OF 0.192 S

FIG. 3

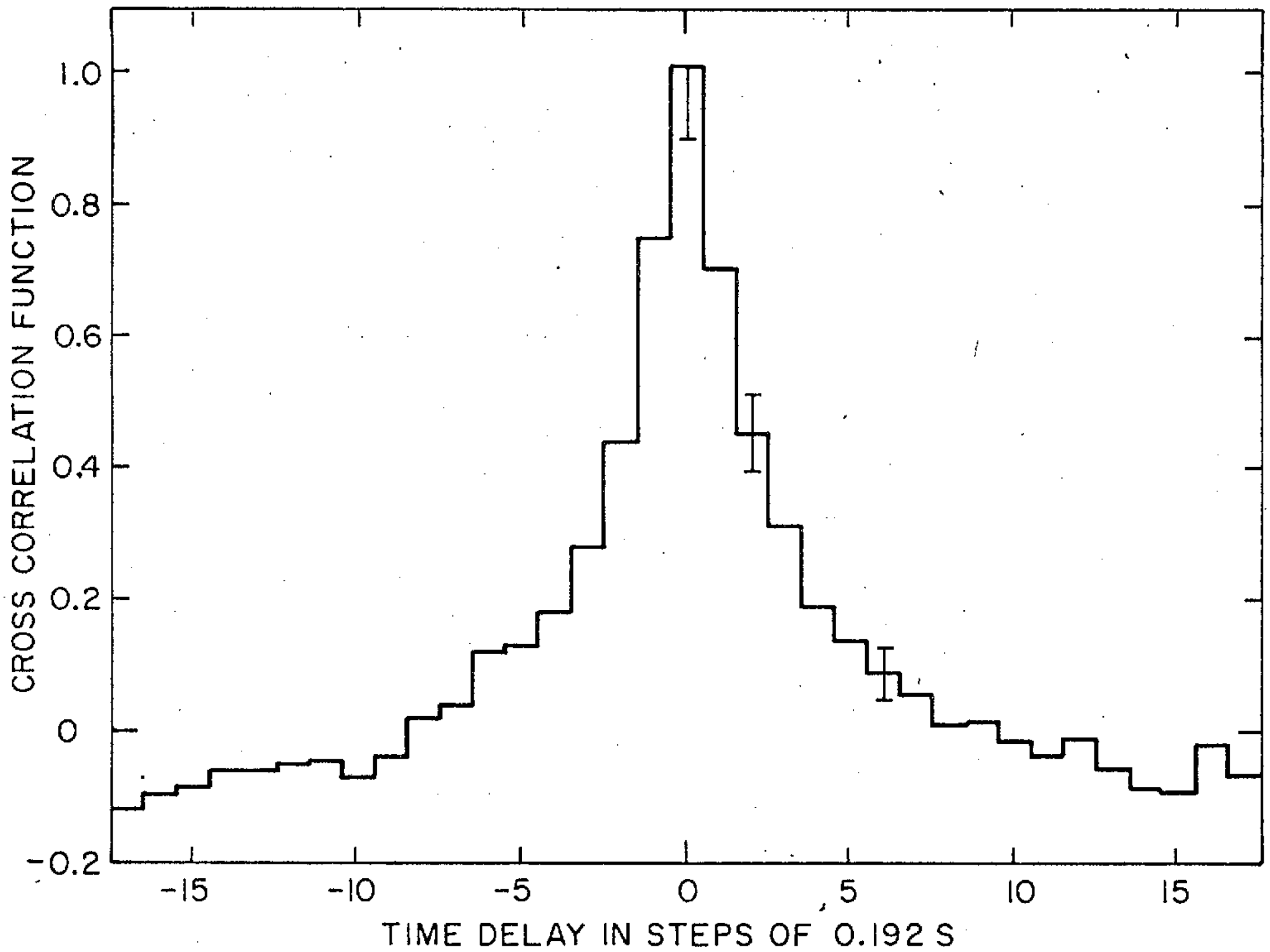

CROSS CORRELATION FUNCTION
1.0
0.8
0.6
0.4
0.2
0
−0.2
−15
−10
−5
0
5
10
15
TIME DELAY IN STEPS OF 0.192 S

FIG. 4