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EVIDENCE FOR MULTIPLE PERIODICITY IN THE  
X-RAY EMISSION FROM CYG X-1

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ABSTRACT

X-ray data from a rocket-borne exposure to Cyg X-1 confirm indications of periodicity obtained from UHURU. However, our data are inconsistent with a single periodic component at 73 msec, and are most easily reconciled in terms of at least two harmonic components at lower frequencies.

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## I. INTRODUCTION

In view of the very exciting report of 73 ms pulsation from Cyg X-1 by Oda, Gorenstein, Gursky, Kellogg, Schreier, Tananbaum, and Giacconi (1971), we report here a temporal study of a rocket exposure to this source obtained on September 21, 1970. In the above mentioned rocket flight, several sources in the Cygnus-Serpens region were examined in detail and will be reported elsewhere. The timeliness of the Cyg X-1 measurement is what has prompted this separate communication.

## II. EXPERIMENTAL DETAILS

The data are obtained in two multi-anode, multi-layer proportional counters, each with  $2^\circ \times 8^\circ$  FWHM collimation and with net areas of  $650 \text{ cm}^2$ . In the top layers of each counter there is three-sided anti-coincidence for each  $1/2$ " cell, and four-sided anti-coincidence in the lower layers. The bottom layer and all anodes adjacent to the side walls are used only for anti-coincidence. One of the counters was filled with P10 (90% argon, 10% methane), and the other with xenon-methane in like proportions. The operating range of the argon counter was 1.6 - 24 keV, and that of the xenon counter was 2 - 40 keV. Both counters had windows of 1 mil aluminized mylar supported by the collimators.

The data were obtained in a 50 kbit/sec PCM format which has been described in detail elsewhere (Boldt, Desai, and Holt, 1969). The important point here is that each data word has a temporal resolution of approximately  $320 \mu\text{sec}$ , during which time a single event may be pulse-height analyzed and up to 32 analyzeable events may be scaled

(analyzeable here means that such events meet all the threshold and anti-coincidence requirements of true x-ray events). The pulse-height-analyzed events therefore have a dead-time of  $\sim 320 \mu\text{sec}$ , while the scaled events have a dead-time of less than  $3 \mu\text{sec}$ .

The exposure to Cyg X-1 was comprised of a single scan across the source at a roll rate of approximately  $0.5^\circ/\text{sec}$ . As the scan was performed using the narrower collimation of  $2^\circ$  FWHM, the total exposure to the source was about 8 seconds (4 seconds FWHM). The maximum instantaneous total counting rate at the apex of the triangular collimator response was approximately  $2100 \text{ sec}^{-1}$  from both detectors, about a factor of twenty in excess of the diffuse plus internal background measured when off the source. This signal-to-noise is further improved if we use a more stringent set of selection criteria for the data. For example, if we restrict ourselves to only pulse-height-analyzed data in the first layer of the xenon counter in the pulse-height range 2 - 8 keV, the maximum instantaneous counting rate to Cyg X-1 is in excess of  $500 \text{ sec}^{-1}$ , a factor of forty above the counting rate when the source is not in the detector field of view.

### III. TEMPORAL ANALYSIS

We have performed two independent temporal analyses of the Cyg X-1 data in search of the 73 msec pulsation reported by Oda, et al. (1971). We have used a Cooley-Tookey algorithm to analyze the data harmonically, and have fast-folded the data as described in our search for temporal variations in Sco X-1 (Boldt, Holt, and Serlemitsos, 1971). In no

cases do we achieve agreement with the postulation of a periodicity of 73 msec.

In the case of the harmonic analysis, we have used the scaled counts, adding zeroes contiguously at the end of the Cyg X-1 exposure in order to obtain  $\sim 0.1$  Hz resolution; this should not alter the relative significance of true peaks in the periodogram. This approximation to the power density spectrum is displayed in Figure 1 out to  $\sim 10$  Hz; no significant power was detected at higher frequencies. In particular, there was no indication of any power in the vicinity of 73 msec.

We cannot fully interpret all of the power, some of which is undoubtedly due to noise in coincidental conjunction with true periodic components during the finite time of our exposure to Cyg X-1. That true periodicity is present seems assured, as a like analysis of our exposure to Cyg X-2 during the same flight, which differed only in that the counting rate at maximum was approximately one-half that from Cyg X-1, showed no significant power above  $\sim .5$  Hz (in fact, the periodogram was completely consistent with the triangular window of the source exposure which serves to spread the spectral peaks of truly significant periodic components to  $\sim 0.2$  Hz in width).

The eight peaks indicated in the figure have been interpreted quite simply in terms of a two-fold periodicity, one modulating the other. In this case we can write the analytic identity (neglecting phases which are not reflected in the power spectrum):

$$\begin{aligned} & \{A + \cos [2\pi\alpha t]\} \cdot \{B + \cos [2\pi\beta t]\} = \\ & = AB + A \cos [2\pi\beta t] + B \cos [2\pi\alpha t] + \\ & \quad + \frac{1}{2} \cos [2\pi(\alpha+\beta)t] + \frac{1}{2} \cos [2\pi(\alpha-\beta)t]. \end{aligned} \quad (1)$$

The indicated peaks in the spectrum represent  $\alpha, \beta, (\alpha+\beta), (\alpha-\beta)$  and their first overtones.

Some further evidence for this interpretation is afforded by Figure 2, where we have plotted the count rate of the pulse-height-analyzed data in 20.5 msec intervals for the Cyg X-1 exposure. We emphasize that the data are not raw; they have been filtered by smoothing with a running sum of four such points to bring out lower frequency components for purposes of illustration. We suggest that the primary components  $\alpha$  and  $\beta$  (where the latter represents an amplitude modulation of the former) can be crudely estimated by eye and are in agreement with our interpretation of the periodogram.

We further tested the data for periodicity using the fast-fold algorithm and  $\chi^2$ -analysis technique described in Boldt, Holt, and Serlemitsos, 1971. The pulsed fraction  $f$  which should be observable at a probability corresponding to  $n$  standard deviations is given by

$$\left(\frac{f}{1+f}\right)^2 \approx \frac{\delta}{1-\delta} \frac{n(2P)^{1/2}}{N}, \quad (2)$$

where  $\delta$  is the duty cycle of the pulse expressed as a fraction of the period,  $P$  is the number of temporal resolution elements in the trial



period, and  $N$  is the total number of x-ray events used. In searching for an unknown periodicity, we generally use  $5\sigma$  as the criterion for statistical significance. In the case of a "known" period, we can ease the restriction to  $3\sigma$  if the number of trial periods in the vicinity of the suspected period is  $\approx 100$ . Our analysis program for Cyg X-1 typically accepts in excess of 5000 events, and we vary the number of temporal bins per period between 40 and 80. All possible periods between 12.8 msec and 409.6 msec were searched, and no  $5\sigma$  results were achieved for periods  $\approx 230$  msec. In the vicinity of 73 msec, there were no  $3\sigma$  results. This would place an absolute upper limit of  $\sim 10\%$  on the pulsed fraction at 73 msec (i.e. for  $\delta \approx .5$ ). For a narrower pulse (i.e. for  $\delta \approx .1$ ), the upper limit to the pulsed fraction at 73 msec would be  $\sim 3\%$ . The light curve we can construct by folding is not good enough for a determination of the pulse shape, as we are limited by both statistics and an imprecise knowledge of the actual period owing to the limited time we spend on the source. Figure 3, which corresponds to a  $>5\sigma$  result in the fast-fold analysis, at a frequency of  $(\alpha + \beta)$ , illustrates this inadequacy in our data. Light curves at the other three basic frequencies are similarly lacking a sharp single pulse, but appear to have a roughly sinusoidal variation.

#### IV. DISCUSSION

We summarize our results as follows:

1. The discovery of periodic fluctuations in the intensity of Cyg X-1 by Oda, et al. is confirmed.



2. The fundamental periodicity (or periodicities) is not in the tens of milliseconds, but in the hundreds of milliseconds.
3. The absolute upper limit to the pulsed fraction at 73 msec is  $\sim 10\%$ .
4. We require more than one fundamental period to account for our data.
5. If equation (1) truly describes the periodic behavior of the x-ray emission of Cyg X-1, fundamental periods of  $\sim 290$  msec and  $\sim 1.1$  sec account for the significant power at these periods, at  $\sim 230$  msec and  $\sim 390$  msec, and at the first overtones of all four.
6. The requirement of low frequency multiple periodicity (statement 4) is quite independent of the attempt at its interpretation (statement 5).
7. The interpretation we suggest presents rather imposing theoretical difficulties. Not only are we asking for a "pulsar" of lower frequency than at least one class of pulsar emission models can comfortably explain (Pacini, 1971), but we are also asking for independent periodic modulation of this pulsed emission component. The mathematical model is equivalent to a rotating pulsar beam of period  $\alpha$ , where the axis of rotation nutates (or the elevation angle of the beam direction oscillates) with period  $\beta$ .

#### ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

1. Periodogram of spectral density versus frequency. The probability of white noise exceeding the power expressed in the units of the ordinate of the figure is approximately  $10^{-2 \times (\text{power})}$ .
2. Pulse-height-analyzed data plotted as a function of time. Note that the data is smoothed by plotting 82 msec accumulations each 20.5 msec.
3. Scaled data folded into 15 bins at the highest of the four primary frequencies,  $(\alpha + \beta) = 232$  msec. The above "light curve" gives a deviation from the expected  $\chi^2$  for a random sample which has a probability equivalent to rejecting the random hypothesis at the  $5\sigma$  level.

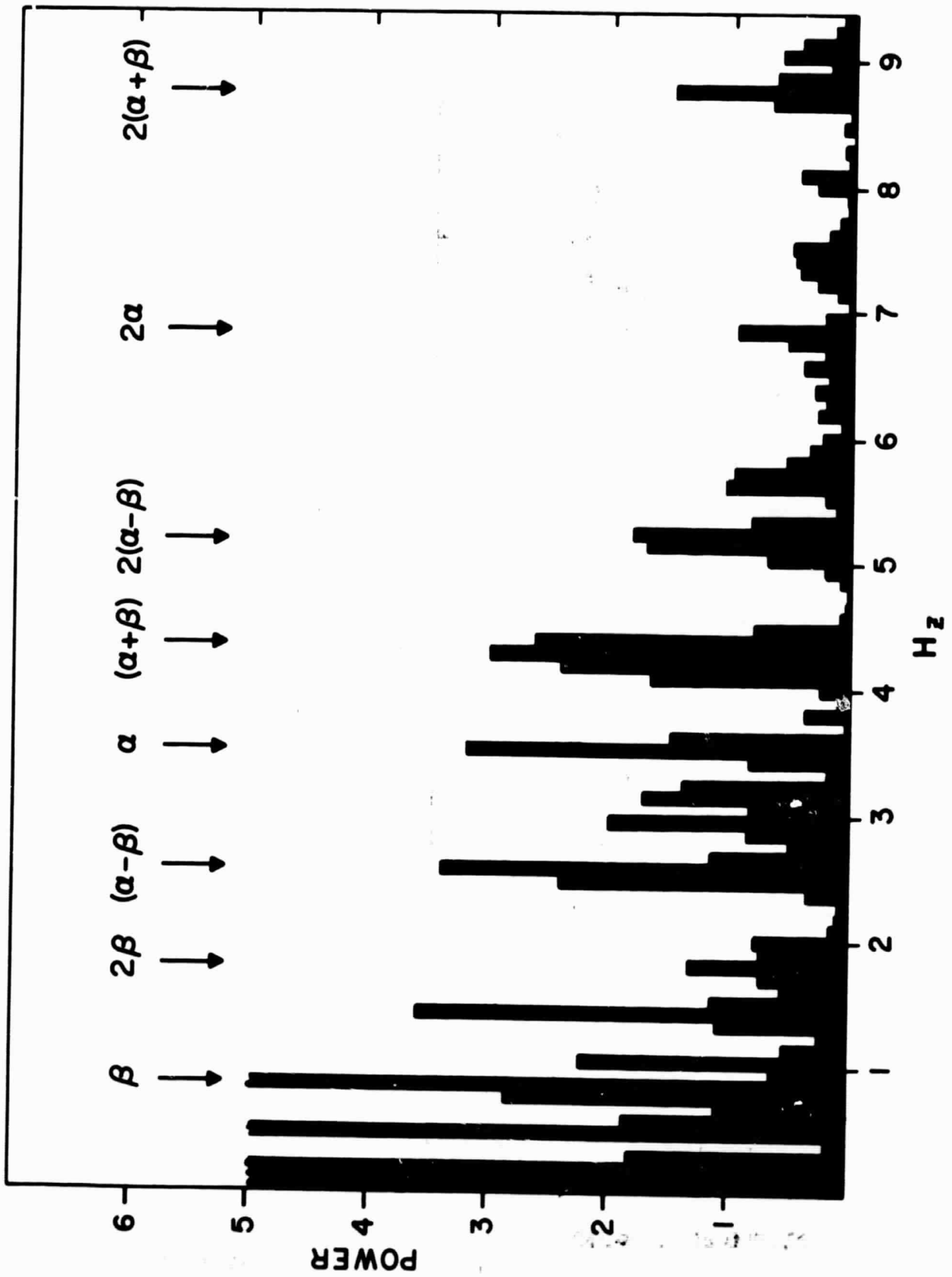


FIGURE 1

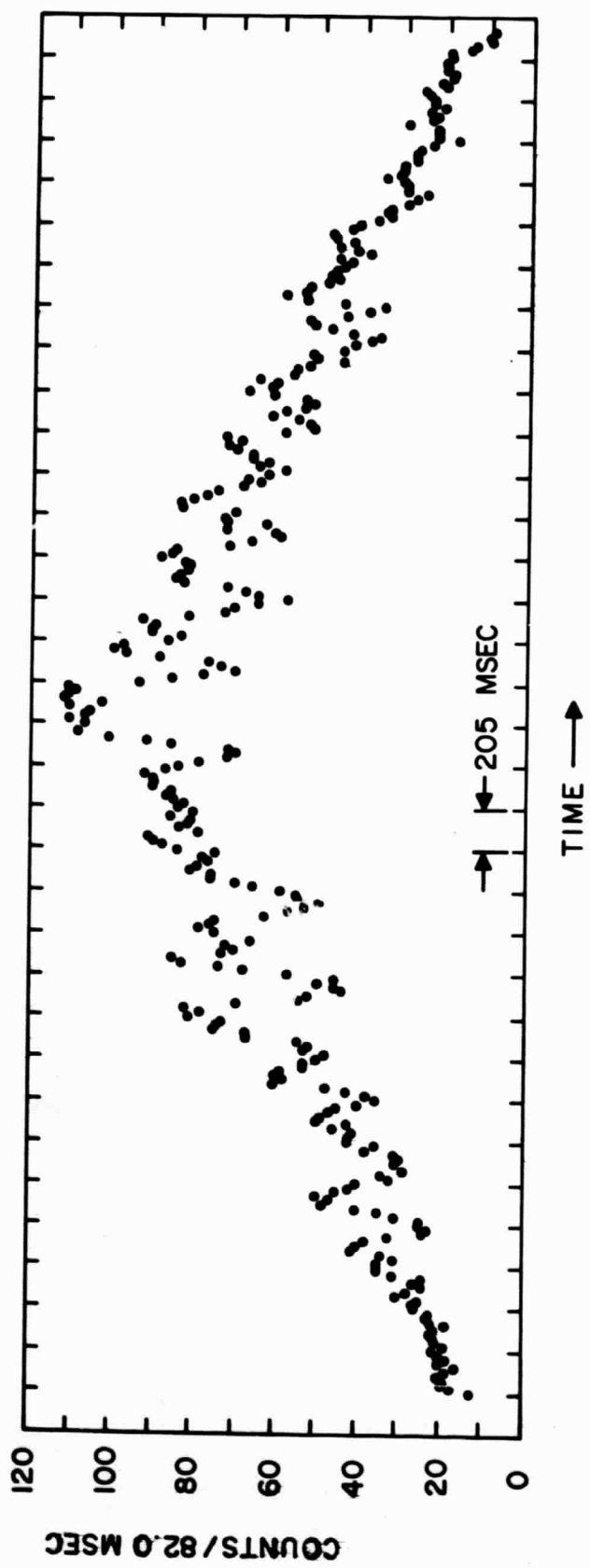


FIGURE 2

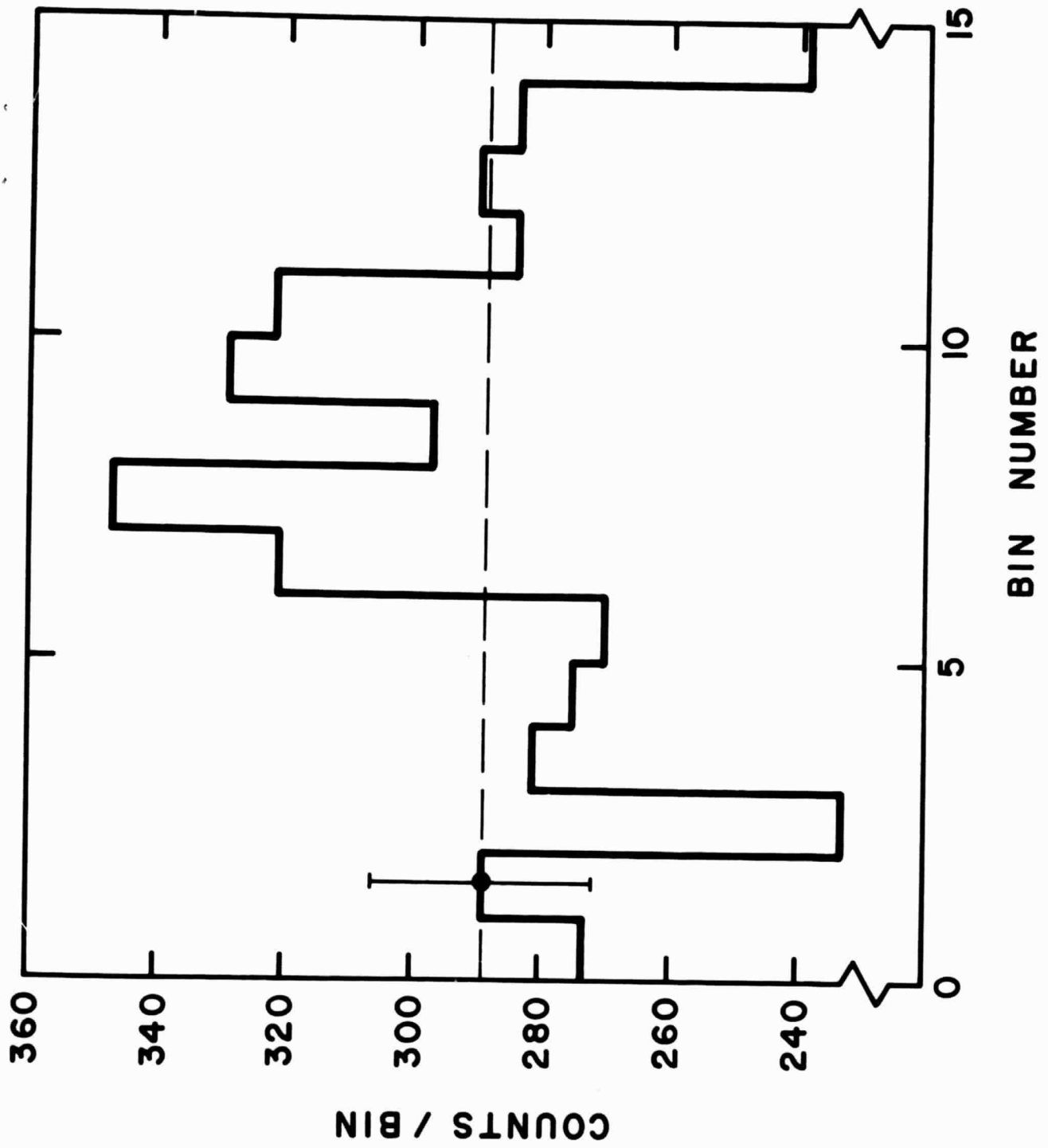


FIGURE 3