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## Long-Term Studies With the Ariel-5 ASM: I. HER X-1, VELA X-1 and CEN X-3

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LONG-TERM STUDIES WITH THE ARIEL-5 ASM  
I. HER X-1, VELA X-1 AND CEN X-3

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ABSTRACT

1200 days of 3-6 keV X-ray data from Her X-1, Vela X-1 and Cen X-3 accumulated with the Ariel-5 All-Sky Monitor are interrogated. The binary periodicities of all three can be clearly observed, as can the  $\sim 35$ -d variation of Her X-1, for which we can refine the period to  $34.875 \pm .030$ -d. No such longer-term periodicity  $< 200$ -d is observed from Vela X-1. The 26.6-d low-state recurrence period for Cen X-3 suggested by Chester (1978) is not observed, but a 43.0-d candidate periodicity is found which may be consistent with the precession of an accretion disk in that system. The present results are illustrative of the long-term studies which can be performed on  $\sim 50$  sources over a temporal base which will ultimately extend to at least 1800 days.

Subject headings: X-rays: binaries -- X-rays: sources

## I. INTRODUCTION

The Ariel-5 satellite was launched on October 15, 1974, with a complement of six X-ray astronomy experiments (c.f. Smith and Courtier, 1976). One of these, the GSFC All-Sky Monitor (ASM), has monitored the sky continuously since that time, albeit at a sensitivity which is relatively poor (i.e. typically, one-tenth the intensity of the Crab nebula for integration times of the order of one day). The extent of the data base (now more than three years) has enabled us to investigate the long-term behavior of many sources and, in particular, to search for long-term ( $> 1$  week) periodicities which are unavailable for interrogation to experiments which have exposures of much shorter duration. This is the first in a series of papers which will be devoted to such study.

The ASM is described in detail by Holt (1976), and an exhaustive discussion of data treatment and systematics may be found in Kaluziński (1977). The important parameters are that  $> 80\%$  of the 3-6 keV sky is monitored with a temporal resolution of  $\gtrsim 100$  minutes, a spatial resolution on the celestial sphere of  $\sim 80$  square degrees, and an effective area of  $\lesssim 1 \text{ mm}^2$ . A typical 100-minute spacecraft orbit gives  $\sim 20$  counts for a source as intense as the Crab nebula, with surrounding source-free resolution elements containing  $\sim 3$  background counts. Clearly, the experiment suffers from relative insensitivity even before source confusion is considered, in general. For regions of sky where source confusion is not a problem (e.g. near Her X-1), we can utilize a point-response technique unambiguously. In more confused regions (e.g. near Cen X-3),

we segment the data into three categories: those for which we have a consistent measure for both the source in question and for the contributions from nearby sources, those for which we expect that the contribution from nearby sources may be underestimated (so that the source measure is really an upper limit), and those for which the surroundings may well dominate our "measure" of the source intensity. We have found that the exclusion of the latter category alone allows us to achieve a sensible data base for sources which would almost never be isolated in the first category.

Previously reported results from the ASM have, typically, involved relatively gross effects (e.g. transient sources, marked intensity changes in strong sources). These results were either insensitive to possible long-term systematics, or were based upon data which were carefully selected and corrected. We attempt, here, to extend the capability of the ASM data base to the interrogation of sources which are nominally below the quoted sensitivity of the experiment. Detailed study of 1200-d records of some 50 source positions have resulted in the illumination of unanticipated long-term systematics. This study has allowed us to develop computer-generated data selection criteria and long-term systematics correction which we apply here in an attempt to interrogate the ASM data base to as low as source intensity level as results will demonstrate to be feasible.

We have chosen, for this initial study of  $\sim 1200$  days of ASM data,

the three binaries Her X-1, Vela X-1 and Cen X-3; the reasons are three-fold. First, this choice allows us to demonstrate the integrity of the data base via the "rediscovery" of already known periodicities in sources which are nominally an order of magnitude below our advertised sensitivity, in regions of sky having differing levels of source confusion. Second, we can comment on tentative periodicity which has been reported in the literature, but has been unconfirmed. Third, we may uncover new timescales for variability in these sources.

## II. DATA ANALYSIS

The data of Figure 1 represent the 1200-day light curves of the three subject sources from mid-October 1974 to late-January 1978. Each point represents data accumulated for slightly more than one week (exactly 5, 1 and 4 binary cycles of the sources exhibited in the three traces, respectively). The 34.9-day variation of Her X-1 is discernable to the practiced eye, but no other periodic effects on timescales  $< 200$  days in any of the three sources are obvious from Figure 1.

The data were interrogated via Fast-Fourier transforms for periodic modulation on all timescales  $> 5$  hours. The shorter timescales ( $< 2.4$  days) were searched by binning the data in a uniform 2.4-hour grid, with unfilled bins given the overall average value. This search was performed over each third ( $\sim 400$  days) of the total record separately. In addition, the longer timescales were interrogated more efficiently with FFT's over the entire 1200-day record with a 1.2-day grid, so that there were fewer unfilled bins and the statistical significance of each filled bin was typically bettered by a factor of 3.

The only known periods which were consistently observed with high statistical significance in all these interrogations were the 34.9-day variation in Her X-1 and the 8.96-day variation in Vela X-1. The 2.09-day variation in Cen X-3 could not be consistently detected in all samples with high confidence, and the 1.7-day variation in Her X-1 could not be detected with any confidence whatsoever (although it could be extracted from the high-state-only data). The fact that we can easily observe the 4.8 hour variation in Cyg X-3 (c.f. Holt et al. 1976b) implies that our apparent decrease in sensitivity with decreasing period is a strong function of source intensity, and must arise from the less-than-perfect differential background correction we must apply to a severely quantum-limited situation (typically, the few counts per orbit of estimated background may exceed the source contribution from each of the three sources discussed here).

With respect to possible source periodicities in addition to the well-known values mentioned above, we do not see any evidence for other periodicity in Her X-1 or Vela X-1 over the range  $\sim 2$ -200 days. It is difficult to place specific limits in general, as they depend upon the shape of the variation as well as the period, but Figures 2 and 3 should be useful in estimating the specific effects to which we are sensitive.

Cen X-3, because it suffers from more potential source confusion in the ASM than do the other two, is considerably less well-monitored; the fraction of filled bins in the 1.2-day FFT interrogation of Cen X-3 is only 38%, compared to 67% for Vela X-1 and 84% for Her X-1.

Nevertheless, the 2.09-day light curve displayed in Figure 3 indicates that true periodicity in the data can be verified. It is significant, therefore, that we find no evidence for the 26.6-day periodicity suggested by Chester (1978) for off-state recurrences. We do find, however, a marginally significant periodicity at  $\sim 43$  days (as well as another at  $> 200$  days, but the duration of our data record for such a long period is  $< 6$  cycles). Figure 4 demonstrates the presence of a 43.0-d effect in our Cen X-3 data record, and the absence of a 26.6-d effect. As a measure of the reproducibility of the 43-day candidate effect, the data of Figure 1 have been studied cycle-by-cycle in a simple manner: for each of 24 contiguous candidate cycles in the data record, we counted the number of cycles for which the minimum was coincident with the ephemeris for the average effect illustrated in Figure 5 (within a phase range of  $1/4$ ), the number of cycles for which it was in the remaining  $3/4$  phase range, and the number of cycles for which we could not clearly decide upon either the first or second category (usually because of incomplete coverage). The results of this straw poll were 14, 4 and 6, respectively, so that the effect we observe cannot be ascribed to the chance coincidence of a few low points.

### III. DISCUSSION

The present Her X-1 data define a binary period with a  $1\sigma$  uncertainty of  $\sim 5 \times 10^{-4}$ -d, which is clearly not competitive with that which can be obtained from Doppler analysis of the 1.24-s pulsations. In the case of the 34.9-d variation, however, it is the length of the temporal baseline which determines the uncertainty in the period. Without a



sharp resolvable temporal feature in the 34.9-d cycle, the best period determination which can be made from the present data alone is  $34.875 \pm .030d$ . This uncertainty is approximately four times better than has been reported previously (Holt et al. 1976a; Giacconi et al. 1973). It is gratifying to note that the computer-corrected light curve of Fig. 3 is almost identical to that generated previously from the first 600 days of hand-corrected data (Holt et al. 1976a). It should be noted, however, that there may be an apparent systematic offset of  $< 0.01 \text{ cm}^{-2} \text{ sec}^{-1}$  (corresponding to  $\approx 5$  UHURU counts). Since all high-sensitivity measurements of Her X-1 (of which we are aware) at 34.9-d phases corresponding to the right-most 4 bins of the light curve are consistent with an intensity which is  $< 5 \text{ Ucts}$  (S. Pravdo, personal communication), we must assume that the computer-generated data bases for any sources we attempt to study may have baseline uncertainties of approximately this magnitude. Furthermore, we also must concede that features that might be marginally significant with more subjectively selected data (e.g. the feature  $\sim 180^\circ$  out-of-phase with Her X-1 34.9-d maximum) may well be obscured by the inclusion of lesser quality data in analysis. Nevertheless, we prefer to search and test for candidate effects with as large and as objectively selected a data base as possible, in order that those effects which persist will almost certainly be ascribable to the X-ray sources rather than peculiarities in the data selection.

Our Vela X-1 analyses would seem to illustrate this last point rather nicely. Although the 1200-d light curve of Figure 1 exhibits

obvious variability, its fast-Fourier transform in Figure 2 detects only the 9-d binary period as a persistent modulator of the source intensity. The binary period light curve of Figure 3 is of the characteristic shape previously reported (c.f. Watson and Griffiths 1977), but note that the increased source confusion near Vela X-1 (relative to Her X-1) has resulted in an additional baseline intensity, as the eclipse center is at level of  $\sim 10$  Ucts. Our period determination has an uncertainty which is approximately an order of magnitude larger than that of Ogelman et al. (1977), so that we have used the period of the latter authors to fold the data in Figure 3.

The Cen X-3 data are somewhat sketchier in coverage than are those for Her X-1 and Vela X-1, and the more pronounced baseline shift in the 2.09-d light curve of Figure 3 testifies to the increased source confusion problem. The data are plotted at the period of Fabbiano and Schreier (1977) for the epoch 1972 September 24.492 corresponding to eclipse center. Their estimate of the rate at which the period decreases (on the average) would result in a period at the center of our data accumulation interval which differs by  $\sim 7 \times 10^{-5}$  d from the 1972 period. The shape of the plotted light curve is totally insensitive to a period change of this order, but the phase of minimum should shift  $\sim 1/5$  of a bin width to the left of the arrow which indicates  $\phi = 0$  for the 1972 ephemeris. Clearly, we can neither confirm nor deny the reality of this average binary period change with time.

Figure 4 illustrates our inability to detect any modulation at 26.6-d, as well as the appearance of the candidate effect at 43-d (which was the most significant modulation detected in the fast-Fourier transform

of the total record). The FWHM (breadth) of the chi-square peak is considerably in excess of that of the "calibration" peak for Her X-1 included in Figure 4. If both the 43-d Cen X-3 and 34.9-d Her X-1 modulations had the same light curve shapes over their respective periods, the expected ratio of chi-square peak breadths would be  $\sim 1.7$  (note, from Figure 1, that the effective Cen X-3 record is  $\sim 10\%$  shorter). The actual ratio is almost twice this large, which implies one of four possibilities. First, the candidate effect may be an artifact of the finite data sample, and may not reflect a true periodicity in the source. Second, the effect may be real but persist for only  $\sim$  one contiguous half of the total data record. Third, the candidate effect may not be strictly reproducible, and the finite number of cycles (and gaps) have not all "averaged out" to a completely unbiased sample. Fourth, the "period" may actually change systematically throughout the exposure owing to a true dynamic effect in the physical system. We can not exclude any of these possibilities with certainty, and shall consider the consequences of the third (which is the most straightforward, if not necessarily the most likely explanation). This assumption is, to some extent, justified by the well-established aperiodic intensity variation obvious in Figure 1 and observed on timescales smaller than one binary orbit by many observers (cf. Schreier et al. 1976).

Chester (1978) has suggested that such a long-period variation might be reconcilable with an accretion disk in the Cen X-3 system. Such a disk would be immediately commensurate with the shorter timescale variations (e.g. absorption dips) observed from the source, and would allow consistency between the measured spin-up rate and the prevailing

theoretical wisdom (cf. Fabbiano and Schreier, 1977). Chester's literature search of the extant Cen X-3 data suggested regularly occurring lows each 26.6 days, which period is inconsistent with the data presented here. We obtained, from the author, a table of the data used for his 26.6-d analysis in order to check for consistency with the 43.0-d period which we obtain. Simply folding these data at 43.0-d in a manner similar to the one in which the present data are folded resulted in a minimum in phase with that of Figure 5, but we do not consider this supportive of the case for a true 43.0-d effect. This is because we were able to obtain minima at least as significant at other periods in these older data, which consist of a distinctly heterogeneous and incomplete sample. Since it is clear from the present data alone, however, that the 43.0-d minima are not strictly reproducible, we have not attempted any further analyses of the earlier data.

Analogy between the 35-d period in Her X-1 and the 43-d candidate period in Cen X-3 is immediately obvious, perhaps even more so in view of the numerical coincidence between the ratio of these periods to the system binary periods (20.5 for Her X-1 vs. 20.6 for Cen X-3). The existence of an accretion disk in a system which is almost certainly dominated by stellar-wind accretion is less likely than in a Roche-lobe overflow system (cf. Shapiro and Lightman 1976), but the average rotation period speedup is most easily reconciled with such a hypothesis. The Her X-1 disk clearly defines its 35-d variation, as the source is totally masked by the disk for  $\sim 2/3$  of the cycle. If we assume a geometry for Cen X-3 which is the operational inverse of that for Her X-1 (i.e.

a "thin" disk which partially masks the source from our view with relatively small duty cycle), it is conceivable that we would expect to observe its intensity modulation only on the average over many cycles, as stellar wind variations would dominate the short-term intensity profile.

#### IV. SUMMARY

We have interrogated 1200 days of data from the Ariel-5 All-Sky Monitor at the celestial locations of Her X-1, Vela X-1 and Cen X-3. All periodicities from these sources in excess of 1.5-d which have been reported in the literature are observable, with the exception of the Cen X-3 26.6-d low-state occurrence period reported by Chester (1978). We find, instead, evidence for a candidate period of 43.0-d.

The present Her X-1 and Vela X-1 data are entirely consistent with previously reported effects in the emission from these sources, and do not significantly impact existing models. The new results from these two sources are a refinement of the 34.9-d period ( $34.875 \pm .030$ -d), and a total lack of significant periodic modulation in the emission from Vela X-1 in the range 10-200 days.

The Cen X-3 data exhibit 2.087-d modulation at the expected period and phase, and appear to be modulated with a 43.0-d period, as well. We interpret this modulation as circumstantial evidence for the presence of an accretion disk, but this interpretation is not unique. We suggest that the reality of this effect can be tested with observations of Cen X-3 from experiments with modest spectral resolution which have observed Cen X-3 many times at varying 43-d phases. Even though the intensity effect we observe may often be masked by wind-dependent

intensity variations, we would assume that the observed continuum spectra coincident with our ephemeris for minimum should systematically be deficient at lower energies. UHURU and Ariel-5 SSI, which have observed Cen X-3 on many occasions in the past, have energy resolution which is sufficient to provide this crucial test. Lastly, we note that the simplest interpretation of this effect in terms of disk precession would also suggest a similar spectral effect at midphase or, alternatively, a disk precession period of 96 rather than 43 days.

The present results provide encouragement for further long-term analyses of the ASM data. The apparent transparency of the analysis techniques to the differential noise and insensitivity of the experiment which plague shorter term studies, reflected in our ability to extract "true" periodicity without substantial contamination, makes an extension of these techniques to other (less well-studied) sources plausible. Ultimately, we expect to similarly interrogate  $\sim 50$  sources, over a data base which is expected to extend over 1800 days.

## REFERENCES

- Chester, T. J. 1978, Ap. J. (Letters) 219, L77.
- Fabbiano, G. and Schreier, E. J. 1977, Ap. J. 214, 235.
- Giacconi, R., Gursky, H., Kellogg, E., Levinson, R., Schreier, E. and Tananbaum, H. 1973, Ap. J. 184, 227.
- Holt, S. S. 1976, Ap. Sp. Sci. 42, 123.
- Holt, S. S., Boldt, E. A., Kaluziński, L. J., Serlemitsos, P. J. and Swank, J. H. 1976a, Nature 263, 484.
- Holt, S. S., Boldt, E. A., Serlemitsos, P. J., Kaluziński, L. J., Pravdo, S. H., Peacock, A., Elvis, M., Watson, M. G. and Pounds, K. A. 1976b, Nature 260, 592.
- Kaluziński, L. J. 1977, Ph.D. Thesis, University of Maryland.
- Ogelman, H., Beuermann, K. P., Kanbach, G., Mayer-Hasselwander, H. A., Capozzi, D., Fiordilino, E., and Molteni, D. 1977, Astron. Ap. 58, 385.
- Schreier, E. J., Swartz, K., Giacconi, R., Fabbiano, G., and Morin, J. 1976, Ap. J. 204, 539.
- Shapiro, S. L. and Lightman, A. P. 1976, Ap. J. 204, 555.
- Smith, J. F., and Courtier, G. M. 1976, Proc. R. Soc. London 350, 421.
- Watson, M. G. and Griffiths, R. E. 1977, Mon. Not. R. Astron. Soc. 178, 513.

## FIGURE CAPTIONS

Figure 1 - 1200-day 3-6 keV light curves of Her X-1 (1656+35), Vela X-1 (0900-40), and Cen X-3 (1118-60). Each point represents the average intensity observed for  $\sim 8.5$  days, and are accumulated over precisely 5, 1 and 4 binary periods of the three sources, respectively.

Figure 2 - Fast-Fourier transform of the 1200-d record of Vela X-1 in 1024 1.17-d bins. Displayed are all of the 512 frequency components with normalized power exceeding 3.22. The probability  $\phi_1$  that any frequency component will have power exceeding  $P_0$  is  $\exp(-P_0)$  if there is no true periodicity in the record, so that a threshold of 3.22 should result in 4% of the 512 frequencies exceeding this threshold (there are actually 18 points which do, with 20 expected). The probability  $\phi_2 = 512\phi_1$  plotted on the right is interpretable as that for which noise may give a peak of this magnitude for any arbitrary (i.e. not specified a priori) candidate. For Vela X-1, where the candidate period is, in fact, specified a priori, the formal probability that the large 8.96-d peak is noise-induced is  $\sim 10^{-8}$ . The two right-most peaks are the first two harmonics of the 8.96-d peak.

Figure 3 - ASM data folded at previously reported periods. In all cases, the error bar displayed is  $\pm 1\sigma$  and is representative of that for all bins in the same trace. The



ephemerides of the arrows representing  $\phi = 0$  are, for Her X-1 JD 2,443,386.779, for Vela X-1 JD 2,442,728.430, and for Cen X-3 JD 2,441,584.992. The ephemeris of the start of the 34.875-d trace is JD 2,442,965.0. The plotted 1.7-d Her X-1 data are only those from the maximum (.15 phase range) of the 34.9-d period.

Figure 4 -  $\chi^2$  as a function of trial period at 0.5-d intervals for the Cen X-3 (1118-60) data folded in 10 bins (closed circles), against the hypothesis of a constant source intensity. For comparison,  $\chi^2$  for the same test on Her X-1 (1656+35) data at 0.2-d intervals folded in 15 bins (open circles) are displayed near 35-d. As can be seen, the "noise level" for the 10-bin Cen X-3 trials is considerably in excess of that for the 15-bin Her X-1 trials.

Figure 5 - ASM Cen X-3 data folded at the candidate  $43.0 \pm 0.1$ -d period. The ephemeris of the midpoint of the central minimum-intensity bin is JD 2,442,823.0.

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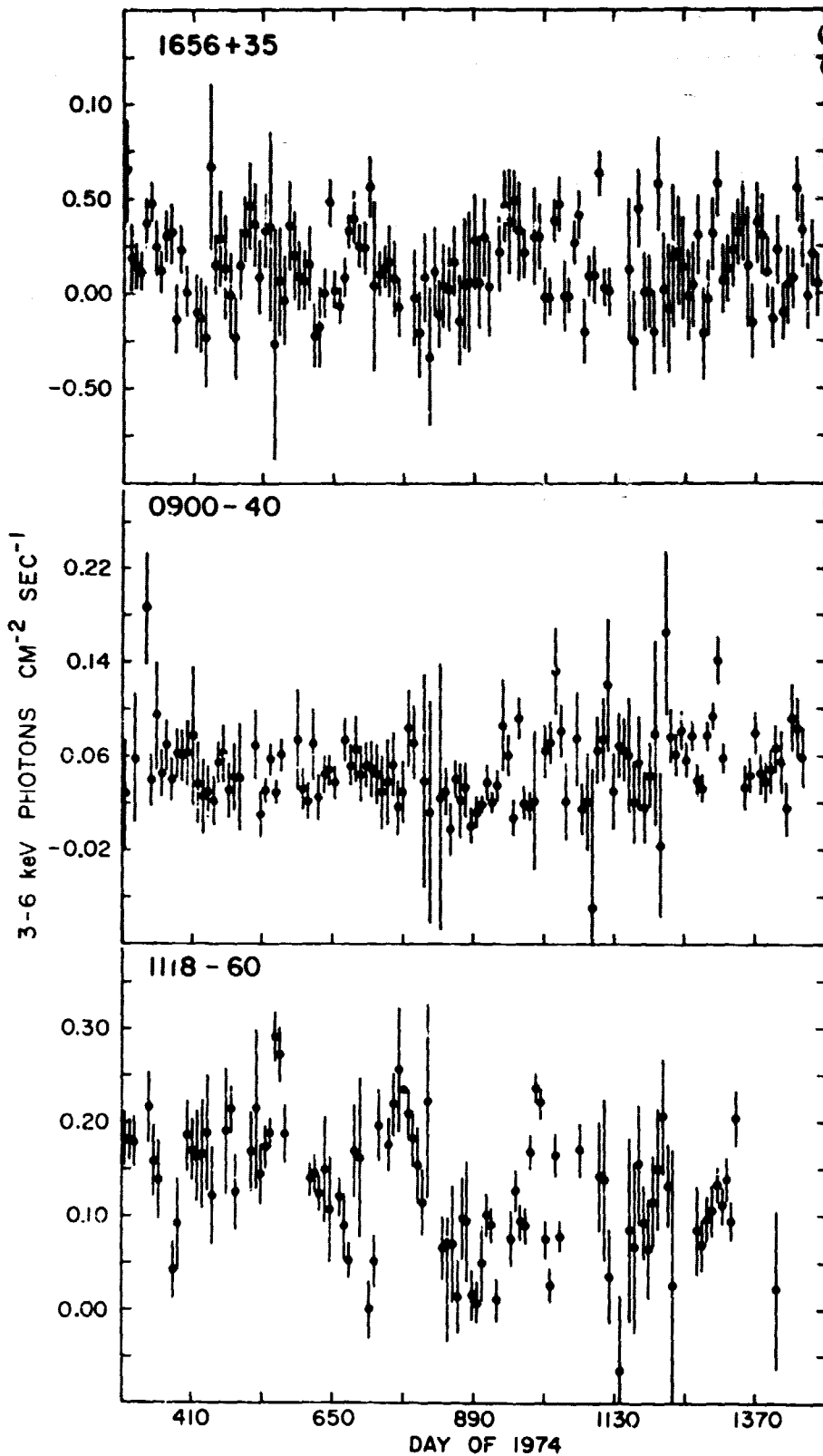


FIG. 1

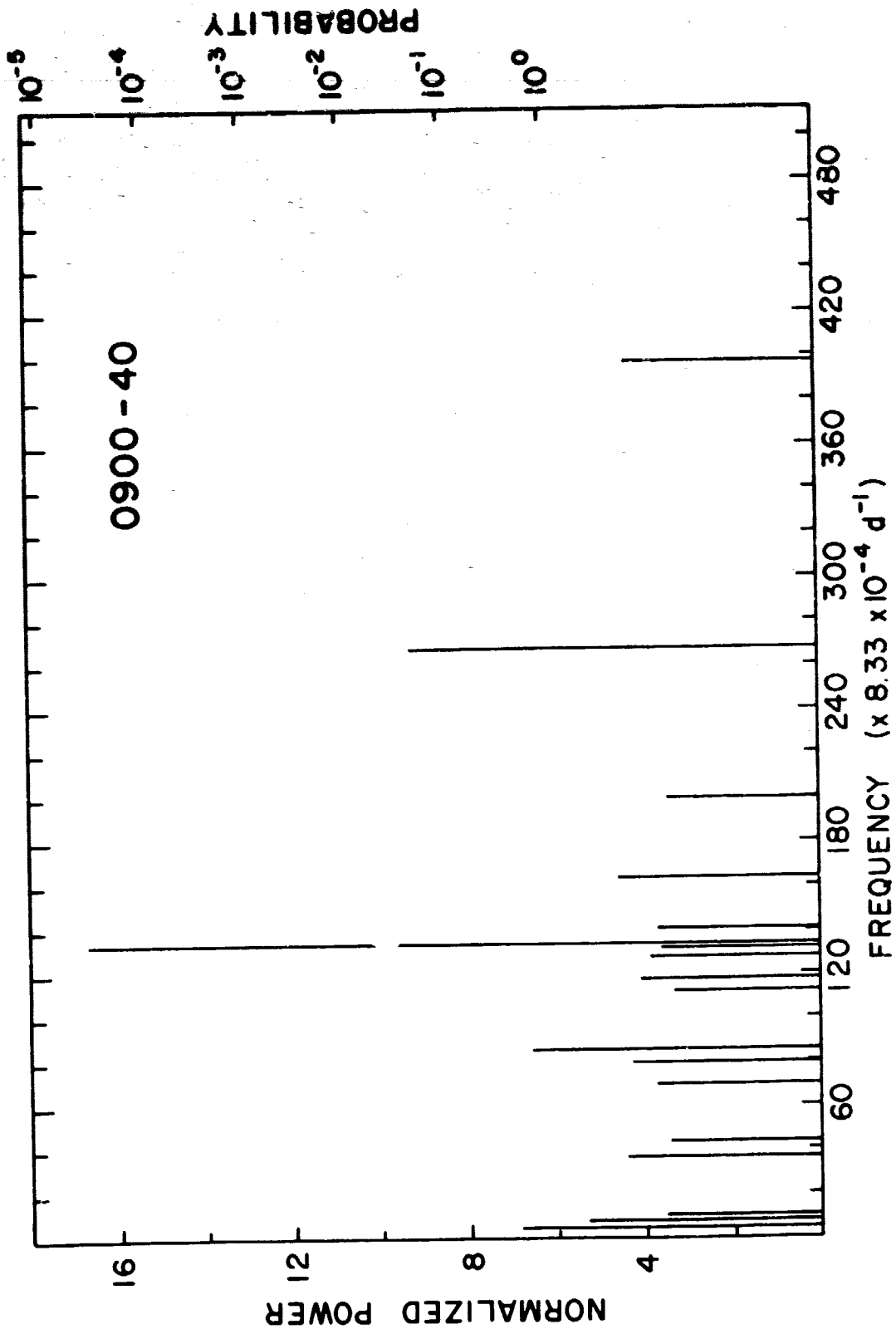


FIG. 2

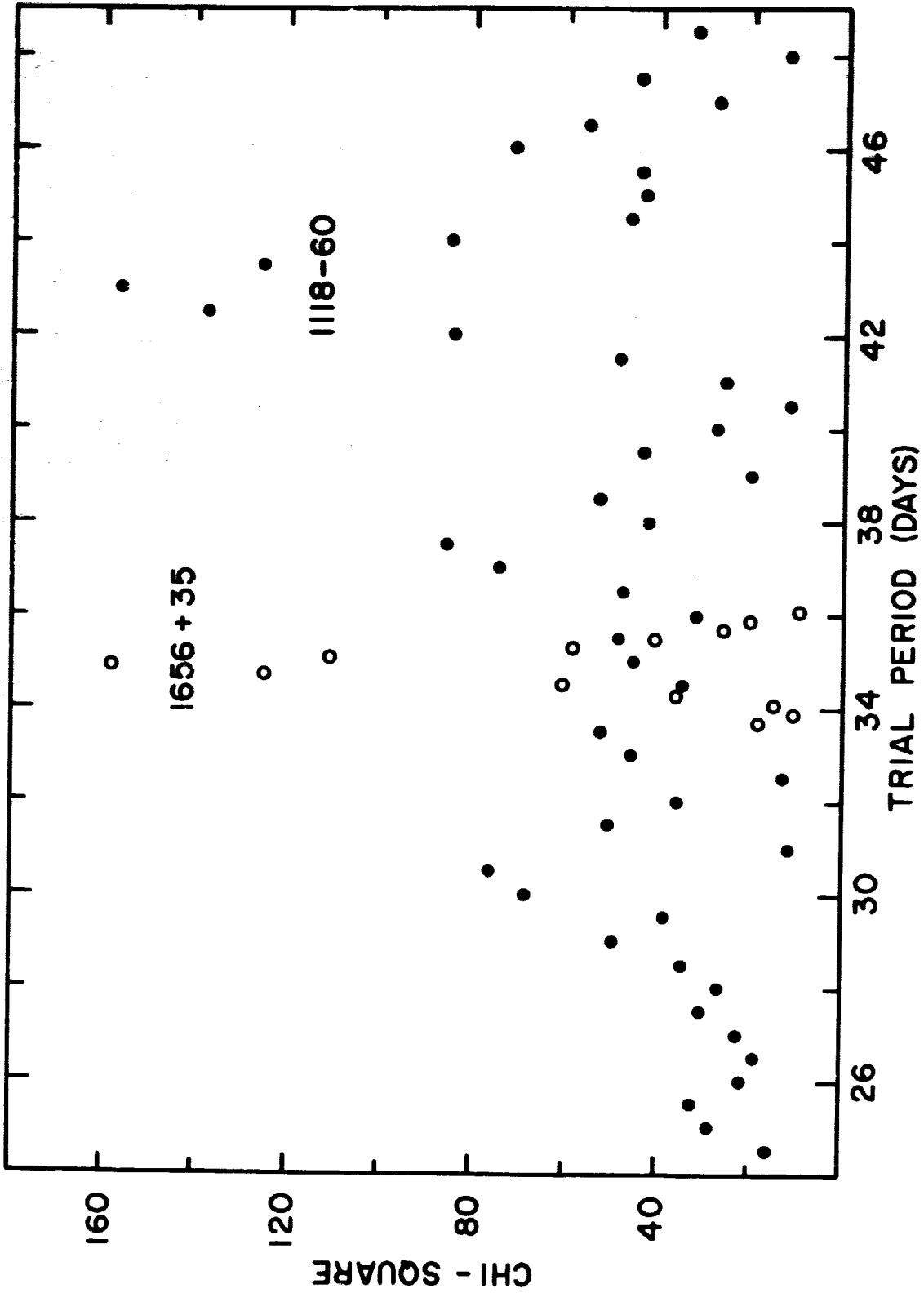


FIG. 3

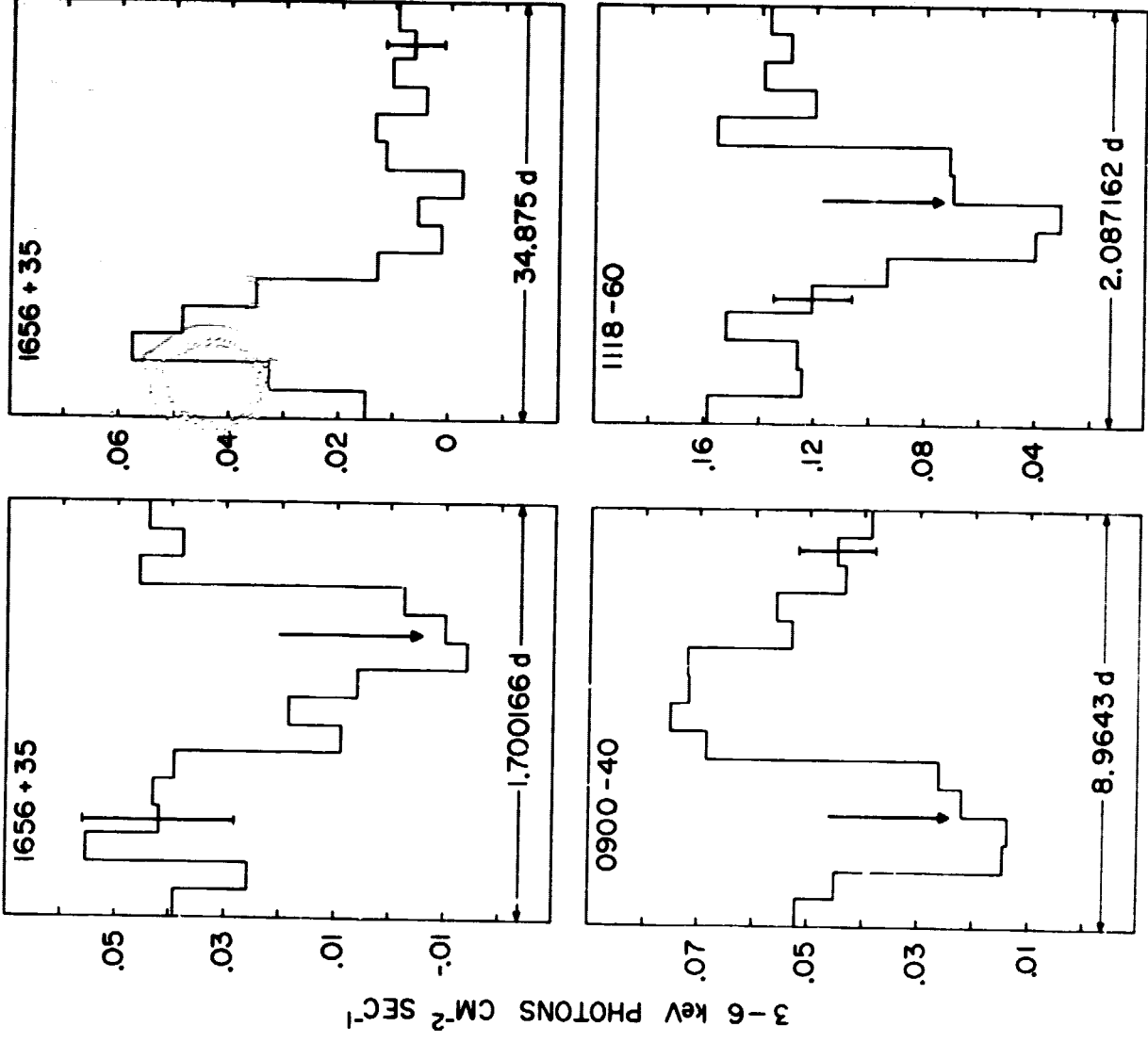


FIG. 4

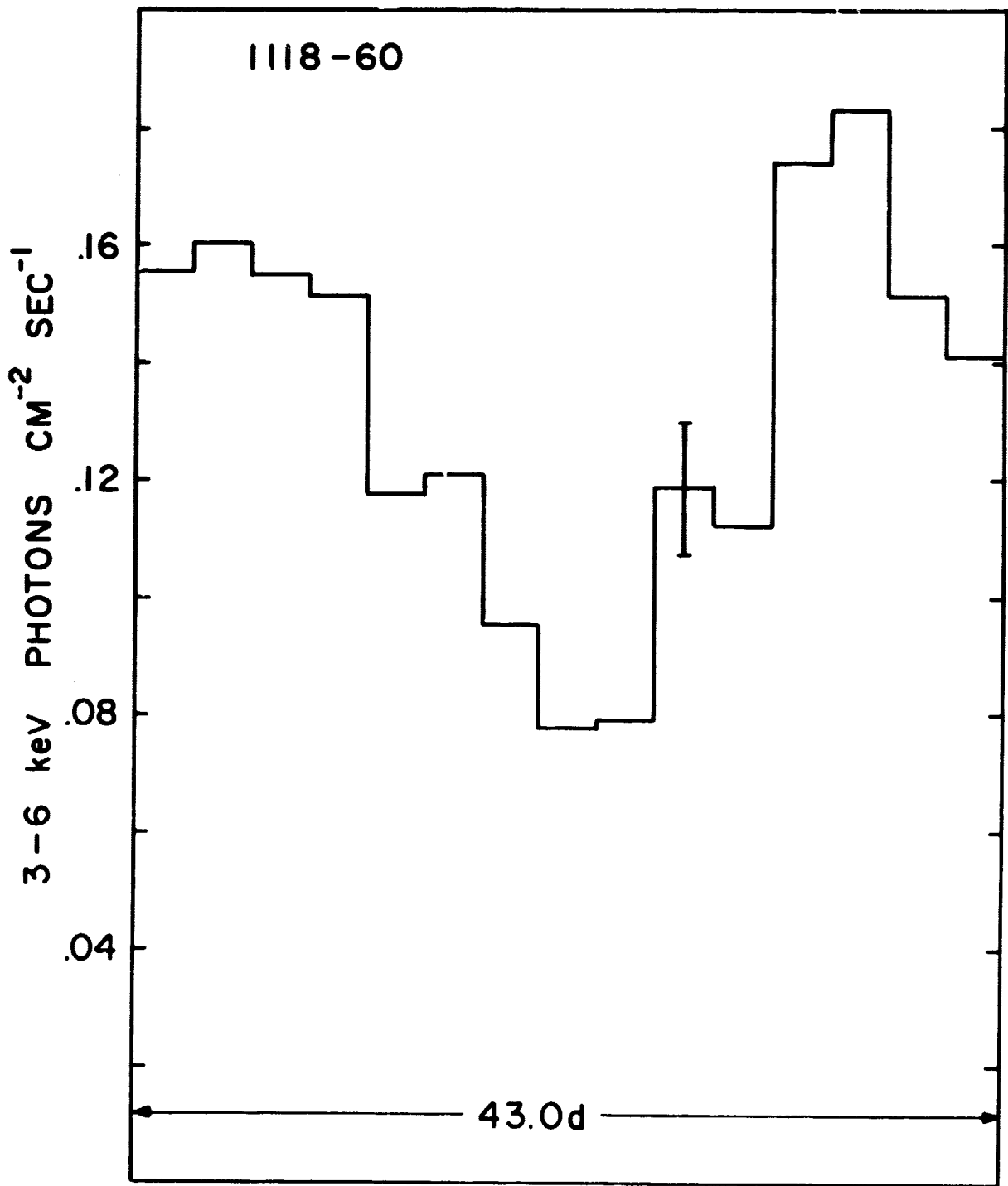


FIG. 5

# BIBLIOGRAPHIC DATA SHEET

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