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LONG-TERM X-RAY OBSERVATIONS OF CEN X-3, GX 301-2 (4U 1223-62), GX 304-1 (4U 1258-61), AND 4U 1145-61

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ABSTRACT

We present 7 year (1969–1976) X-ray time histories for the sources Cen X-3, GX 301−2, GX 304−1, and 4U 1145−61, with 10 day time resolution. Time series analysis confirms the 41.5 day periodicity of GX 301−2 and adds evidence for the previously reported 187.5 day period in 4U 1145−61. A new period of 132.5 ± 0.4 days is reported for GX 304−1. Comparison of our *Vela* data and previous results shows that there may be a significant difference between the photometric and quoted Doppler pulse timing periods for GX 301−2. The periods of GX 301−2, GX 304−1, and 4U 1145−61 are consistent with binary orbital variations. No evidence is found for the 26.6 and 43.0 day periods previously reported for Cen X-3. The 2.087 day eclipse period of Cen X-3 appears with high significance, aliased by the detector sampling period to 20.33 days. High state activity in Cen X-3 repeats with a characteristic (but nonperiodic) timescale of 120–165 days.

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

I. INTRODUCTION

X-ray data from the *Vela* spacecraft provide information about the long-term behavior of celestial X-ray sources for an unequaled time span. The *Vela 5B* spacecraft was launched on 1969 May 23; on board was the XC detector, a scintillator-photomultiplier X-ray detector sensitive to X-rays in the range 3–12 keV. The detector worked until 1979 June 19, a span of 10.1 yr, although data acquisition was incomplete after mid-1976. The collimator was pointed perpendicular to the spin axis of the Earth-oriented spacecraft, which had a nominal spin period of 64 s, and mapped the celestial sphere twice per 112 hr orbit. The collimator acceptance was $6^\circ.1 \times 6^\circ.1$ FWHM, so that a typical source was scanned for 2–3 hr out of every 56. Detector background in the 3–12 keV band was approximately 90% of the signal from the Crab. (1 Crab ≈ 40 counts s^{-1} when centered in the field of view, so that 1 *Vela* count $s^{-1} \approx 25$ UFU.)

Though the wide collimation leads to source confusion in many interesting regions of the sky, good aspect information (to $\pm 0^\circ.2$) allows the deconvolution of individual source intensities. Data accumulations of 1 s from the XC detector were summed into 10 day sky maps (90 days after mid-1976), with each count assigned to a $2^\circ \times 2^\circ$ bin, according to the detector aspect at the central time of the accumulation. The region of the maps containing the sources of interest was fitted to the intensity of the known bright sources, as well as to a residual background and background gradient terms, in order to extract individual source time histories. Quoted intensities are in units of detector counts per second for the source centered in the field of view. Intensity errors are calculated from standard χ^2 considerations. The experiment and analysis technique are described in more detail by Terrell *et al.* (1982), Priedhorsky, Terrell, and Holt (1983) and references therein. The only comparable set of long-term X-ray time histories comes from the *Ariel 5* All-Sky Monitor Experiment (ASM), operational from 1974.8 to 1980.2 (Holt 1976). Unfortunately, the limited telemetry available to that experiment reduced the spatial resolution to about 8° (FWHM); no additional aspect data were available. The All-Sky Monitor is therefore subject to source confusion problems significantly worse than those for Vela.

One particularly interesting collection of bright X-ray sources is to be found in the Centaurus-Crux region of the galactic plane, which includes the bright X-ray sources Cen X-3 (4U 1118−60), GX 301−2 (4U 1223−62), GX 304−1 (4U 1258−61), and the transient 4U 1145−61. Though the four sources, all on the galactic plane, fall within a 12° region of galactic longitude, the analysis technique allows isolation of the individual source time histories. The sky map region bounded by $l = 284^\circ$, $l = 314^\circ$, $b = -10^\circ$, and $b = 10^\circ$ was fitted to yield the intensity of the four sources. Fainter sources not considered in the calculation tend to be included in the inferred intensity of nearby sources. For example, signal from the faint pulsator A1118−61 will most likely be summed into Cen X-3, $1^\circ.3$ away. The independence of the inferred intensities is demonstrated below by the fact that the strong periodicities which we observe do not spill over to the other objects. We are therefore able to present the 7 year (1969–1976) time history of these objects with 10 day time resolution. *Vela* scanning coverage of the Centaurus-Crux region was good: the region was 20° to 40° from the pole of the spacecraft orbit during 1969–1976, so that it was scanned about twice as frequently as sources on the orbital plane.

a) *Cen X-3* (*4U 1118−60*)

The four sources reported are bright and therefore well studied. Cen X-3 was the first accretion-driven X-ray pulsator discovered (Giacconi *et al.* 1971); periodic eclipses and variation in the pulse period led to its identification as a binary system (Schreier *et al.* 1972). The standard model for the system is of a 1 solar mass accreting neutron star, rotating every 4.8 s, in a 2.087 day orbit with a 17 solar mass evolved O star (Hutchings *et al.* 1979). Longer term periodicities have been reported by Chester (26.6 days; 1978) and by Holt *et al.* (43.0 days; 1979). The ASM data reported by Holt *et al.* show no evidence for a 26.6 day variation but seem to show a "marginally significant" modulation of 0.5 of the mean flux at 43 days. The proposed long-term variations are suggested to be the result of precession of an accretion disk, as in the Her X-1 system.

b) *GX 301−2* (*4U 1223−62*) *and GX 304−1* (*4U 1258−61*)

GX 301−2 and GX 304−1 are long-period (699 s and 272 s) hard and variable X-ray pulsators. Both sources were discovered during the rocket/balloon era of X-ray astronomy, but the slow pulsations were not known until analysis of observations by *Ariel 5* and *SAS 3* (White *et al.* 1976; McClintock *et al.* 1977). Pulse timing analysis shows that GX 301 − 2 is in a wide, eccentric binary orbit. White, Mason, and Sanford (1978) derived a period of 40.80 ±0.03 days from their pulse timing data, while Kelley, Rappaport, and Petre (1980, hereafter KRP) found a discrete set of possible periods given by $(456 \pm 1)/n$ days, where n is an integer between ~11 and ~15; KRP gave 35.0 days as the most probable value. Watson, Warwick, and Corbet (1982, hereafter WWC) found evidence for a 41.51±0.05 day period from an analysis of X-ray flare events. WWC also published a table of orbital elements provided by Kelley and Rappaport (1982; see also table 1 of KRP) for an assumed value of $n = 11$, which yields an orbital period of 41.37±0.02 days. The companion to GX 301−2, Wray 977, is a B supergiant of 25–35 solar masses (Parkes *et al.* 1980); the periodic maxima are explained by the variable accretion rate of the neutron star as it travels in its eccentric orbit through the supergiant's wind (KRP).

No orbital period has previously been reported for GX 304−1. A binary companion has been identified; it is a main sequence B star, rotating at near breakup speed (Parkes, Murdin, and Mason 1980). The spectrum is dominated by "shell star" characteristics, indicating considerable mass ejected into an equatorially expanding ring or shell. Some of the mass lost is presumably accreted by the neutron star to drive the observed X-ray emission. Pulse timing data set a limit $P_{\rm orb} \geq 18$ days for the expected companion mass function $f(M_2) = 10$ solar masses ($P_{\rm orb} \geq 13$ days for any $f(M_2) \geq 1$ solar mass; McClintock *et al.* 1977). No third periodicity has been suggested for either GX 301−2 or GX 304−1.

c) *4U 1145−61*

4U 1145−61, discovered by *Uhuru* in an outburst to 0.07 Crab, is actually two hard X-ray pulsators which are separated on the sky by only 20′ (Lamb *et al.* 1980; White *et al.* 1980). Coincidentally, the periods of the two objects are very similar. The southern source, which retained the 4U designation (also known as 2S 1145−619), has a 292 s period; 1E 1145.1−6141 has a 297 s period. The *Vela* analysis sums the signal from these two objects. Pulse timing analysis of the two pulsations sets limits on the allowed binary periods; for all $f(M_2) \geq 1$ solar mass, any binary period for 4U 1145−61 must be greater than 34 days, while any binary period for 1E 1145.1−6141 must exceed 12 days (White *et al.* 1978). However, Ilovaisky, Chevalier, and Motch (1982) report a period of 5.648 days from optical photometry. The companions to the two pulsators are B stars. 4U 1145−61 has a B1 Vne secondary, while the 1E source is identified with a reddened B supergiant classified as B2 I. Watson, Warwick, and Ricketts (1981, hereafter WWR) report a 187.5 day outburst period for 4U 1145−61. The source has brief (~ days) outbursts to about 0.1 Crab at 187.5 day intervals; position information from the *Ariel 5* SSI experiment locates the outbursts at the southern source. This period is presumed to be that of an eccentric binary orbit. An extremely bright outburst to ~1 Crab was observed by *SAS 3* in 1978 May (Jernigan *et al.* 1978). Timing data showed a period of 297 s, which would place the outburst at the 1E source, but there may be problems with period aliasing (J. G. Jernigan 1981, private communication 1981, quoted in WWR). *Ariel 5* SSI position measurements from the decline of the same outburst place it at 4U 1145−61 (WWR).

II. TIME HISTORIES, FOURIER TRANSFORMS, AND DISCUSSION

Figure 1 shows the results of the four source fit to 10 day maps of the Centaurus-Crux region. Each time history consists of 257 10 day averages, spanning mid-1969 to mid-1976. The error bars plotted are 1 σ confidence limits.

Direct Fourier transforms of the data of Figure 1 are shown in Figure 2. A secular trend has been removed from the data by fitting a cubic; the residuals were weighted by their statistical errors before transformation. The transforms cover the frequency span up to the Nyquist frequency (18.263 yr^{-1}). Fourier power is in arbitrary units. A year is a convenient time unit for the long time spans reported here; for our purposes, 1 "Julian" year is defined as 365.25 days.

a) *Cen X-3*

The time history of Cen X-3 shows recurrent high ($\gtrsim 10$ counts s^{-1}) and low states, which repeat on a time scale of 0.3–0.5 yr. The high states of 1974.9, 1975.5, and 1976.0 agree with maxima observed by the *Ariel 5* All-Sky Monitor (Holt *et al.* 1979). The Fourier transform shows a broad enhancement at 2.3–2.9 cycles yr^{-1} which is apparently associated with the high-low activity visible in Figure 1. The width (in frequency) of the enhancement shows that it is not a regular periodicity. Also, transforms of the two halves of the time series show different peaks in the region 2.3–2.9 cycles yr^{-1}. The high-low activity thus shows a characteristic but nonregular time scale of 125–165 days.

The presence of quasi-periodic high states is reminiscent of Her X-1, which shows random phase jitter in its 35 day cycle (Boynton, Crosa, and Deeter 1980). For Her X-1, the 35 day period shows an rms variation of 0.7 days per cycle, for a Q of approximately 50. When fit by a similar model, Cen X-3 has a "clock" that is at least an order of magnitude worse. The mean interval between the maxima from 1972.7 to the end of the data set is 136 ± 25 days (rms scatter); for the entire data set, the recurrence time is 125 ± 41 days, but identification of discrete maxima in the period 1969–1972 is ambiguous. In any case, Cen X-3 has a Q of 3–6, significantly worse than Her X-1. If the high-low activity in Cen X-3 represents a disk precession, the stochastic processes which contribute to phase noise are significantly more important than for Her X-1.

The largest peak in the Fourier transform falls at 17.956 ± 0.016 cycles yr^{-1} (20.341 days; this and all subsequent error limits are standard deviations). This frequency corresponds to the beat between the 2.08714(± 0.00002) day eclipse period of Cen X-3 (Fabbiano and Schreier 1977), and the 2.32596(± 0.00003) day cycle with which the *Vela* spacecraft scanned Cen X-3 (half the satellite orbital period). Because of precession of the pole of the spacecraft orbit, different parts of the sky are scanned with slightly different periods. The observed frequency is in excellent agreement with the predicted beat frequency of 17.968 ± 0.003 cycles yr^{-1} (20.327 days). The presence of this beat at an accessible frequency is a fortunate coincidence; no other strong, regularly periodic source has a low-frequency beat of this significance (see below for a weaker result from SMC X-1).

We find no evidence for the suggested 43.0 and 26.6 day periods (Holt *et al.* 1979; Chester 1978). No peak is found at either frequency in the Fourier transform; epoch-folding analysis also gives a null result. To determine the upper limit for a 43.0 day modulation, an artificial signal with a waveform approximating the 43.0 day light curve of Holt *et al.* (1979) was added to the data (i.e., square waveform with 0.4 cycle width of minimum, and amplitude 0.5 of the average signal). A mean Cen X-3 signal of 4.7 *Vela* counts s^{-1} was assumed. The tracer yielded a peak power which would be offscale in Figure 2. A conservative upper limit is that any 43 day modulation of Cen X-3 is less than half that of the Holt *et al.* (1979) light curve; e.g., the modulation is less than 25% of the average intensity. It is possible that the ASM 43 day period represents contamination from GX 301−2, 8° away on the sky, which has a marked 41.5 day period (see below). The ASM map bins have a maximum dimension of 17°; the Cen X-3 signal could thus easily include a contribution from GX 301−2.

b) *GX 301−2 (4U 1223−62)*

Figure 2 shows a strong 41.5 day period in GX 301−2, which confirms the results of White, Mason, and Sanford (1978), KRP (Table 1), WWC, and Kelley and Rappaport (1982). The 35 day period emphasized by KRP can be rejected. Error bounds on the value of the period can be determined from the average Fourier noise power; at 1 σ confidence, the range of acceptable frequencies are those for which $F(\nu) > F(\nu_{\text{peak}}) - 0.5F_{\text{mean}}$, where F is the Fourier power (Middleditch 1976). By this criterion, the first harmonic peak gives $P = 41.41 \pm 0.05$ days, while the second harmonic peak implies $P = 41.56 \pm 0.04$ days, for a best period estimate of 41.50 ± 0.03 days. This can be compared with the results of WWC, who find that flares repeat with a period of 41.51 ± 0.05 days, while pulse timing analysis (constrained to the 41.5 day vicinity by the photometric data) yields $P = 41.37 \pm 0.02$ day (Kelley and Rappaport 1982). The agreement between our result and the WWC flare periodicity is heartening, but there appears to be a significant difference between the pulse timing period and the *Vela* and WWC photometric periods. The *Vela* data, folded at $P = 41.50$ day, have a sharply peaked maximum at epoch JD 2,441,704.7± 0.5 (circa 1973.1). The epoch of maximum is the same for a fold at $P = 41.37$ days. The pulse timing solution, extrapolated back to that epoch, has periastron passage at JD 2,441,714.0± 0.9 (Kelley and Rappaport 1982), so that the photometric maximum precedes periastron passage by 0.224 ± 0.025 cycle. By comparison, WWC report that photometric maximum precedes periastron passage by 0.09 cycle for epoch 1977.0 (maximum at JD

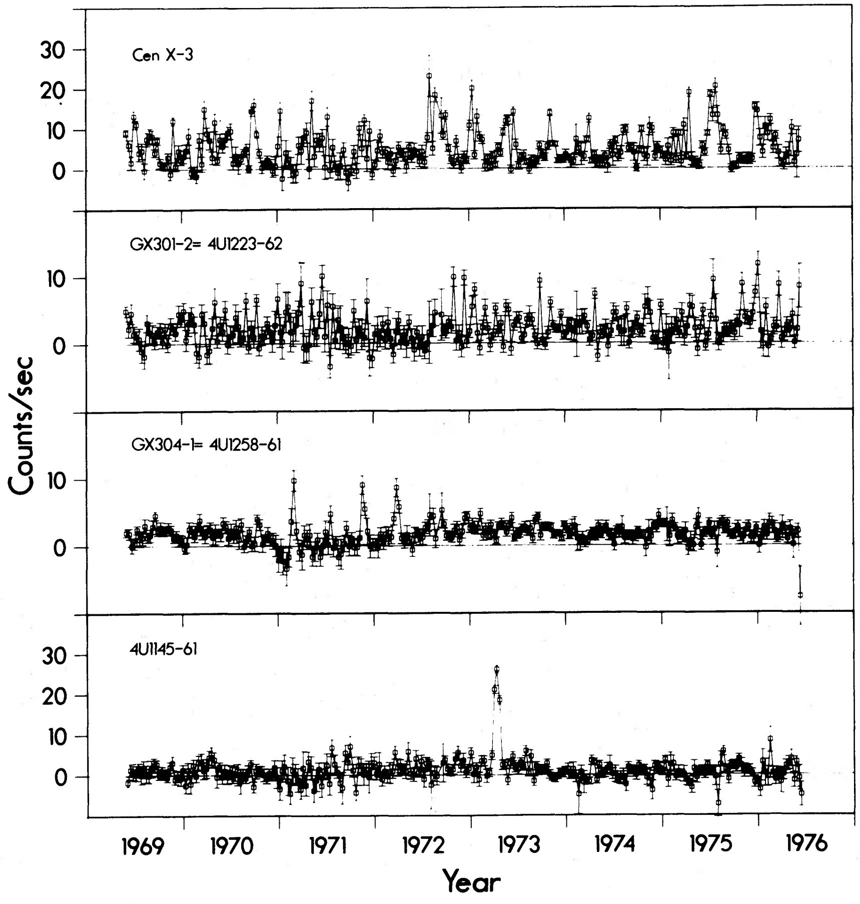

FIG. 1

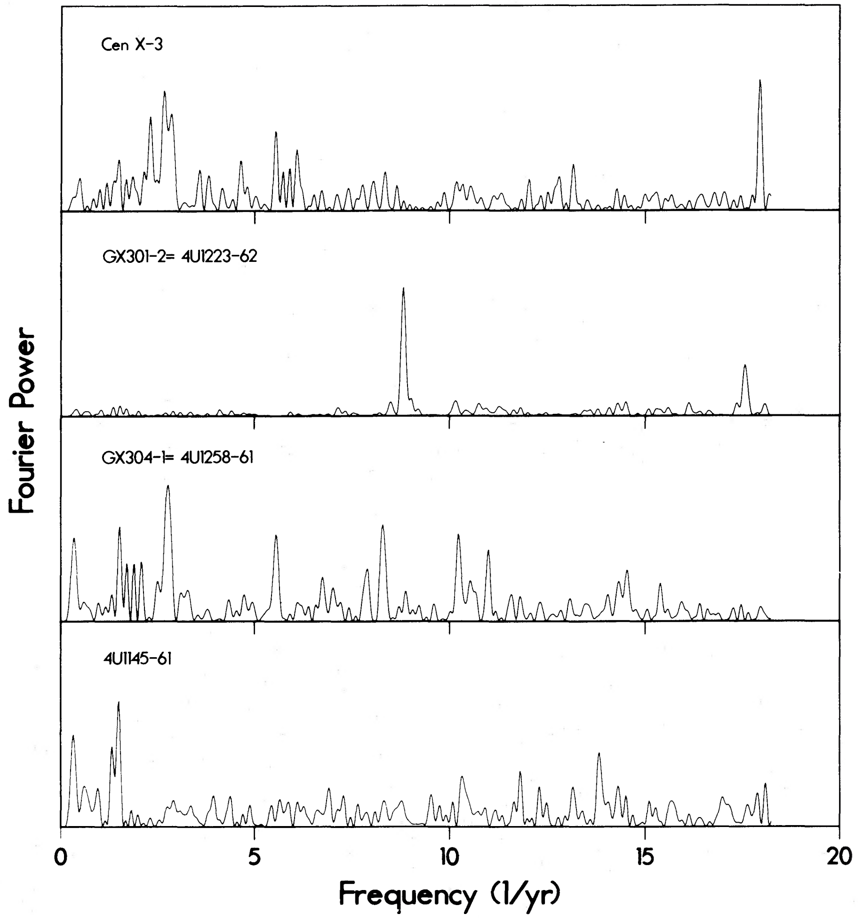

FIG. 2

FIG. 1.—X-ray time histories of Cen X-3, GX 301−2, GX 304−1, and 4U 1145−61, as determined from *Vela 5B* data. Each data point represents a 10 day average; error bars are ±1 σ confidence limits.

FIG. 2.—Direct Fourier transforms of the data of Fig. 1. Data from the 1973 April outburst of 4U 1145−61 have been removed before the transform.

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2,443,158.1 ± 0.7). The times of maximum for the two epochs, separated by 35 cycles ≈ 4.1 yr, imply a photometric period $P = 41.53 \pm 0.03$ days. The difference between the photometric and pulse timing periods is thus found internally in the Vela and WWC data, and also in the relative phase between the two data sets; the three measures of the photometric period can be combined to yield a best estimate $P = 41.52 \pm 0.02$ days.

If the pulse timing period is accurate, we conclude that flare maximum drifts in orbital phase, so that it must not be simply a periastron passage effect. One may spectulate that, if the orbital plane and the axis of the B star do not coincide, flares may occur when the neutron star passes through the equatorial plane of the star. In the equatorial plane, the wind density may be greater, or the wind velocity less, so that the mass accretion rate onto the neutron star is enhanced (White *et al.* 1982). Precession between the stellar rotation and orbit could cause this passage to drift around the orbital period. In this scenario, we observe only the plane passage near periastron, as the mass accretion rate at the far plane passage may be too small to produce an observable outburst. One would predict that, when the outbursts have shifted to the vicinity of 0.25 period after periastron, the outbursts would jump in phase by -0.5 period to the other plane crossing. Alternately, the pulse timing period may be wrong, perhaps biased by changing mass accretion torques during the outbursts.

c) GX 304−1 (4U 1258−61)

The Fourier transform of GX 304−1 (Fig. 2) shows significant signal at the first through fourth harmonics of $\nu = \sim 2.8$ cycles yr^{-1}. Such a transform suggests periodic flaring, to which epoch-folding analysis is most sensitive. Results of the folding analysis (χ^2 test of source constancy versus assumed period for 10 phase bins) are shown in Figure 3, which confirms the periodicity. The major peaks observed are all associated with harmonics or subharmonics of the ~ 2.8 cycle yr^{-1} peak. The best fit period was determined from the Fourier analysis; combining the first four harmonics, we calculate $P = 132.5 \pm 0.4$ days. The estimated error is small because of the strength of the higher harmonics. The epoch of maximum is JD 2,441,675.6 ± 1.5 (1973.0 era); the folded light curve shows a narrow maximum (FWHM = 0.14 cycle = 19 days, when the data were folded into 20 bins). The 10 day binning of the sky maps precludes any better resolution of the peak. It must be noted that a significant fraction of the 132 day signal is derived from a series of large flares in 1971–1972 (cycles -5, -3, -2, -1 with respect to the epoch above). A transform of the data from which these flares have been edited (by eliminating all points above 4.8 counts s^{-1}) shows a 132 day peak of just over half the original power.

A likely explanation for the 132 day period in GX 304−1 is the same as that for long periods in other hard X-ray pulsators: variable mass accretion, due to an eccentric binary orbit. The period is long, but not a record for an X-ray binary (see below). This result is consistent with the limit ($P \geq 18$ days) set by pulse timing data.

d) 4U 1145−61

The time history of 4U 1145−61 (Fig. 1) is dominated by an outburst to ≥ 0.6 Crab in 1973 April, spanning three 10 day bins centered on JD 2,441,785. This outburst, occurring after the demise of the *Uhuru* spacecraft, was previously unreported. High time resolution data have not yet been analyzed to identify (by period) whether the 4U or 1E source is responsible for the outburst. A more finely binned outburst history, and pulsation analysis, will be reported elsewhere. WWR report that the outburst activity in the region comes from the 4U source, based on position measurements; this is circumstantial evidence that the 1973 outburst was also from the 4U source.

Epoch-folding analysis of the 4U 1145−61 data gives evidence for the 187.5 day period proposed by WWR. The magnitude of the 1973 outburst is such that it would dominate Fourier transform and epoch folding analysis of the time history. Accordingly, it has been edited out before the transform of Figure 2, to allow examination of the rest of the data for persistent variations. No evidence for the 187.5 day WWR period is visible in the Fourier transform (Fig. 2); for the regular, sharply peaked outbursts reported by WWR, the Fourier power would be expected to be distributed over a number of harmonics. Epoch-folding analysis is a more sensitive test for such variations and indeed shows a local maximum consistent with $P = 187.5$ days (Fig. 4). In addition, the Fourier transform and epoch-folding analysis both show a broad peak from 1.3–1.6 cycles yr^{-1} (230–280 days). This feature is not a regular periodicity, as it appears only in the last half of the data, and is also too wide in frequency space. It may be a real characteristic time scale in the 4U or 1E source, as in Cen X-3. The narrow 1.95 cycle yr^{-1} peak ($P = 187.5$ days) lies three standard deviations above the local mean power, averaged from 1.6 to 3.0 cycles yr^{-1} (outside the broad peak). All other peaks in the region 2 to 5 cycles yr^{-1} that are as large as the 187.5 day peak can be associated with harmonics and sums of the 187.5 and 230–280 day features. The folded light curve ($P = 187.5$ days; see inset in Fig. 4), shows a single high bin, which cannot be resolved with our 10 day time resolution. The epoch of maximum is JD 2,441,777 ± 5; the WWR maximum, extrapolated to the same epoch, is JD 2,441,769 ± 3, consistent with our maximum. The integrated area

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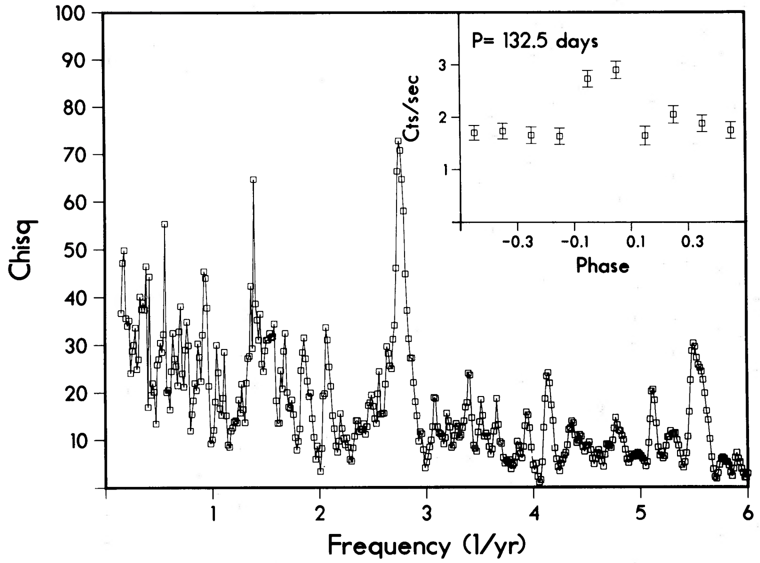

FIG. 3.—Epoch-folding analysis (χ^2 test of constancy vs. fold period, 10 bins) for GX 304−1 (4U 1223−62). Prominent peaks correspond to $\nu = 2.756$ yr^{-1} ($P = 132.5$ days) and the harmonics and subharmonics $\nu/5$, $\nu/3$, $\nu/2$, $3\nu/4$, $3\nu/2$, and 2ν; the inset shows the folded light curve, with zero phase at the epoch of maximum quoted in the text.

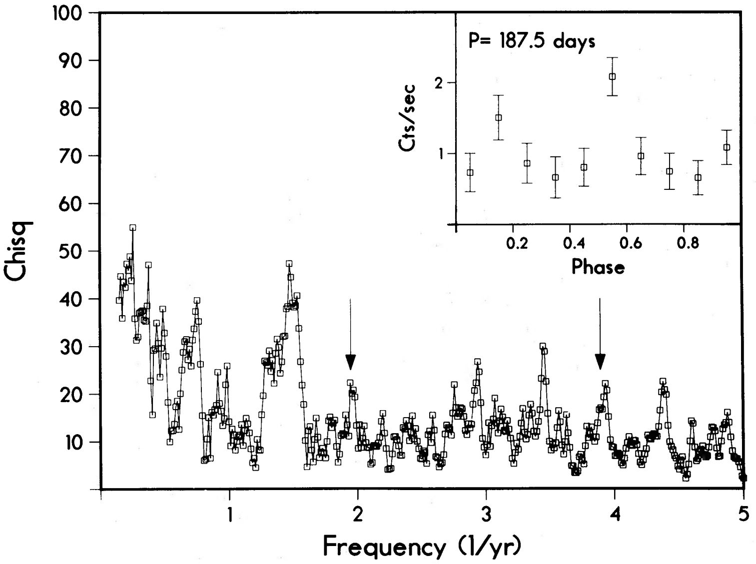

FIG. 4.—Epoch-folding analysis of 4U 1145−61, excluding three 10 day bins during the 1973 outburst. Arrows mark $P = 187.5$ days and its first harmonic (WWR); the inset shows the light curve folded at that period, with arbitrary phase convention.

under the peak in the light curve is ≈ 0.6 Crab days, which is comparable to the average outburst observed by WWR. The presence of a marginally significant local maximum in the epoch-folding analysis, combined with agreement in phase to better than 5%, provides good evidence for the WWR result. The significance of the *Vela* periodicity is not sufficient to allow an improved determination of the period. The large 1973 peak is centered at phase 0.08, according to the WWR ephemeris (0.04 with respect to the *Vela* epoch), and is probably another manifestation of the 187.5 day period.

The Fourier peak at 13.8 cycles yr^{-1} may possibly be explained by the beat between twice the spacecraft scan period for this source (4.6519 day) and the 5.648 ± 0.014 day period for 1E 1145.1−6141 suggested by Ilovaisky, Chevalier, and Motch (1982). A component of the sampling function at twice the scan period exists because of the difference in scan time at opposite sides of the spacecraft orbit, caused by orbital eccentricity. We observe the same beat in the transform of our data for SMC X-1. The well-known eclipse frequency of SMC X-1, 93.837 ± 0.012 yr^{-1} (3.892 days; Liller 1973; Tuohy and Rapley 1975) would be expected to beat with half the scan frequency (78.504 ± 0.001 yr^{-1}, 4.6526 days for SMC X-1) to yield an observed frequency of 15.333 ± 0.012 yr^{-1}. SMC X-1 indeed shows a peak at 15.31 ± 0.03 yr^{-1}, with a 1% probability of random occurrence. The predicted beat frequency for 1E 1145.1−6141 is 13.85 ± 0.16 cycles yr^{-1}, compared to the observed frequency of 13.82 ± 0.03 yr^{-1} (26.43 days). We estimate an $\approx 10\%$ chance that random noise would produce a peak of this amplitude ($5 \times$ mean power) at this predicted frequency, or another equally interesting one. Confirmation of this result must wait for reanalysis of the *Vela* data at higher time resolution. If we assume the peak is real, it implies a refined period for 1E 1145.1−6141 of 5.6455 ± 0.0027 day.

III. CONCLUSION

Three of four sources examined show periods in excess of a month. This result is consistent with the model of these sources as neutron stars, in eccentric orbits around early type stars, accreting matter from the stellar wind. The *Vela* data confirm the suggested period of 41.5 days for GX 301−2 and add evidence for a 187.5 day period in 4U 1145−61. A 132.5 day period, manifested by regular, sharply peaked outbursts, is found for GX 304−1. The suggested 26.6 and 43.0 day periods for Cen X-3 are not confirmed.

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