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LONG-TERM OBSERVATIONS OF X-RAY SOURCES: THE AQUILA-SERPENS-SCUTUM REGION

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ABSTRACT

We present long-term (1969–1976) observations of galactic X-ray sources in the Aquila-Serpens-Scutum region. Data were obtained by the 3–12 keV detector on the *Vela 5B* satellite. The time histories of nine sources were derived from sky maps of this confused region: Scutum X-1, 4U 1823−00, 4U 1915−05, Aquila X-1, Serpens X-1, 4U 1907+09, A1850−087, 4U 1901+03, and 4U 1957+11. These observations reveal new long-term variations for several sources. Aql X-1, which averages about one eruption per year, is shown to have an underlying cycle of 122–125 days, with an rms phase walk of 10% per cycle. A regular 199 day period is observed from the vicinity of 4U 1915−05. This period appears too long to reconcile with the standard model of that system as a low-mass binary with a 50 minute period. The OB system 4U 1907+09 shows a possible 41.6 day period, with substantial phase jitter. We discuss these variations as possible precessions in binary systems.

Subject headings: stars: variables — X-rays: sources

I. INTRODUCTION

Regular intensity modulations on long time scales have been observed for several galactic X-ray sources. A lengthy, continuous data base is essential to a proper search for such variations. Such data are available from the 3–12 keV X-ray detector which flew on the *Vela 5B* satellite. All-sky coverage is available for the period 1969 May to 1979 June, though after 1976 June the data record is sparse because of incomplete telemetry coverage. The celestial sphere was scanned twice per 112 hour *Vela* satellite orbit, with 6°.1 × 6°.1 (FWHM) collimation. The 27 cm^2 detector yielded 1 count s^{-1} for 4.5×10^{-10} ergs cm^{-2} s^{-1} in the 3–12 keV response band. Sensitivity was limited by a detector background which averaged 36 counts s^{-1} (~0.9 Crab).

Scanning data from the period 1969–1976 have been averaged into 10 day all-sky maps. Source confusion is a problem, because of the wide collimation, but aspect information is good to ±0°.2. The maps can be fitted, using the collimator response function, to yield individual source time histories for sources only a few degrees apart. The experiment and analysis technique are described in more detail by Terrell *et al.* (1982), Priedhorsky, Terrell, and Holt (1983), and references therein.

In this paper, the fourth in a series, we report *Vela* observations of sources in the Aquila-Serpens-Scutum region, which comprises the galactic plane between longitudes 20° and 50°. We have previously reported *Vela* observations of Cyg X-1, the Centaurus-Crux region, and A0535+26 (Priedhorsky, Terrell, and Holt 1983; Priedhorsky and Terrell 1983*a*, *b*). Sky maps of the region $16° < l < 52°$, $-18° < b < 14°$ were fit to the intensities of eight sources: Scutum X-1, 4U 1823−00, 4U 1915−05, Aquila X-1, Serpens X-1, 4U 1907+09, A1850−087, and 4U 1901+03, assuming cataloged values for their positions (Bradt and McClintock 1983). The fitting procedure tends to allocate the signal from fainter sources not included in the fit to nearby sources which are included. An additional term in the fit allowed for the intensity of GX 17+2 (at the edge of the map), and other bright bulge sources nearer the galactic center. Other terms allowed for the average map background, and also linear background trends with galactic longitude and latitude. The source 4U 1957+11 is sufficiently isolated from other sources to treat separately; the region $44° < l < 60°$, $-18° < b < 0°$ was fitted to the intensity of this single source plus background terms. The region including the nine sources is plotted in Figure 1, which also shows fainter sources cataloged by *Ariel 5* and *Uhuru*. All the sources on the map are listed in Table 1.

Interesting periodic and quasi-periodic variations are found for the sources Aql X-1, 4U 1907+09, and 4U 1915−05. In § II, we discuss previous observations of these sources, and Ser X-1, Sct X-1, and 4U 1901+03. The *Vela* results are reported and discussed in the light of previous observations and possible models in § III.

II. PREVIOUS OBSERVATIONS

The region under study contains several bright X-ray sources which have been extensively studied. To place the present observations in context, we summarize previous results for

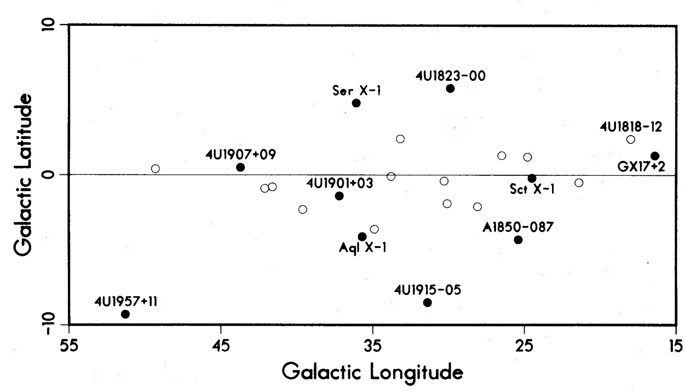

FIG. 1.—Map of the source distribution. The filled circles denote sources that were fitted to produce time histories; the results from GX 17+2 are contaminated by bright sources closer to the galactic center, and so are not reported. Open circles denote faint *Ariel 5* and *Uhuru* sources not included in the fit; any flux from them will be included in the calculated signal for nearby fit sources. All sources in the map are listed in Table 1.

TABLE 1

BRIGHT X-RAY SOURCES IN THE AQUILA-SERPENS-SCUTUM REGION

Source	Galactic Longitude (deg)	Galactic Latitude (deg)	*Uhuru* Flux (counts s^{-1})	*Ariel* Flux[a] (counts s^{-1})
Sources included in fit:				
GX17+2 (4U 1813−14)	16.4	1.3	240–950	...
4U 1823−00	29.9	5.8	28–55	...
Sct X-1 (1833−07)	24.5	−0.2	...	...
Ser X-1 (4U 1837+04)	36.1	4.8	110–320	...
A1850−087	25.4	−4.3	...	3–9
4U 1901+03	37.2	−1.4	up to 87	...
Aql X-1 (4U 1908+00)	35.7	−4.1	up to 200	...
4U 1915−05	31.4	−8.5	10–20	...
4U 1907+09	43.7	0.5	4–20	...
4U 1957+11	51.3	−9.3	17.4	...
Sources not included in fit:				
A1829−10	21.4	−0.5	...	1–3
A1829−06 (possibly Sct X-1)	24.8	1.2	...	2–5
A1840+01	33.2	2.4	...	1–5
A1845−02	30.3	−0.4	...	5–9
A1847−05	28.1	−2.1	...	3–5
A1850+00	33.8	−0.1	...	3–6
A1905+00	34.9	−3.6	...	3–5
A1908+07	41.6	−0.8	...	2–5
A1909+04 (SS 433)	39.6	−2.3	...	2–5
A1918+14	49.3	0.4	...	0.5–3
4U 1812−12	18.0	2.4	10–20	...
4U 1832−05	26.5	1.3	3.3	...
4U 1850−03	30.1	−1.9	5.5	...
4U 1909+07	42.1	−0.9	4.6	...

NOTE.—*Ariel* sources in table are from Seward *et al.* 1976; 4U sources are from Forman *et al.* 1978.

[a] 1 *Ariel* count ~ 2.5 *Uhuru* counts.

Aql X-1, 4U 1907+09, 4U 1915−05, and the bright sources Ser X-1, Sct X-1, and 4U 1901+03.

Aql X-1 (4U 1908+00) is a well-known recurrent X-ray transient, which erupts about once a year to a flux level comparable to the Crab. At other times, it is at least two orders of magnitude fainter (Charles *et al.* 1980). Kaluzienski *et al.* (1977) reported observations of outbursts in 1971, 1973, 1975, and 1976, by *OSO 7* and the *Ariel V* All Sky Monitor, and suggested a recurrence time of approximately 435 ± 40 days. Thorstensen, Charles, and Bowyer (1978*a*, *b*) identified the X-ray source with a 20th mag K star, which flared to 17th mag concurrently with the X-ray outbursts. Their finding suggests a binary model for the system; the 1.3 day X-ray modulation observed during the decay of the 1975 outburst (Watson 1976) is possibly the orbital period. Extensive optical and X-ray observations were made during the 1978 June–August outburst and were interpreted in terms of the "standard" low-mass binary-accretion disk model (Charles *et al.* 1980). The observation of the 1978 outburst, and smaller events in 1977 January and 1979 March (Holt and Kaluzienski 1977; Kaluzienski and Holt 1979), appear to rule out a 435 ± 40 day outburst cycle. The observation of two type I X-ray bursts during the decay of the 1980 May–June outburst (Koyama *et al.* 1981) is, by analogy with other bursters (Lewin and Joss 1981), added evidence for the low mass binary model. No pulsational or long-term periodicity has previously been reported for Aql X-1.

The source 4U 1915−05 is another X-ray burster which is thought to be a low-mass binary. Bursts from the general direction of 4U 1915−05 were first observed by the GSFC *OSO 8* experiment (Becker *et al.* 1977); observations in 1977 June by *SAS 3* (Lewin, Hoffman, and Doty 1977) located the burst source to within a 0.07 deg^2 error box coincident with the steady source, making the identification of the burst source with 4U 1915−05 almost certain. The *OSO 8* spectral data revealed a very hard ($kT \geq 30$ keV) exponential spectrum for both the steady source and the bursts, which makes this source different from the usual, softer spectrum burst sources (Becker *et al.* 1977). White and Swank (1982) and Walter *et al.* (1982) independently discovered absorption dips which recur with a 50 minute period. This period is interpreted as the binary period of a close low-mass system. *HEAO* A-2 spectral data showed $kT = 12 \pm 2$ keV for the steady source, which, though a softer spectrum than implied by the *OSO 8* data, is still a very hard spectrum for a burst source (White and Swank 1982). A 3″ *Einstein* HRI position of the source was determined by Walter *et al.* (1982). Two stars were found within the error circle: a $V \sim 16$ mag G star, and a faint object close to the center of the circle with $R \sim 23$ mag, which was felt to be the most likely candidate. No pulse period is known for 4U 1915−05.

Ser X-1 (4U 1837+04) is a steady galactic bulge source about which little is known. It is bright, with a maximum *Uhuru* catalog flux of 280 counts s^{-1} (Forman *et al.* 1978). It is a burst source (Swank *et al.* 1976; Li *et al.* 1977). The optical counterpart is a faint ($B \sim 19$) blue object (Thorstensen, Charles, and Bowyer 1978*b*), which has been observed to show optical bursts simultaneous with X-ray bursts (Hackwell *et al.* 1979). Ser X-1 shows the soft spectrum characteristic of the bulge sources; *Uhuru* data show $kT = 4 \pm 1$ keV (Jones 1977). Ponman (1981) has suggested a period in the range 3.22–3.55 day for Ser X-1, which is manifested by an approximately

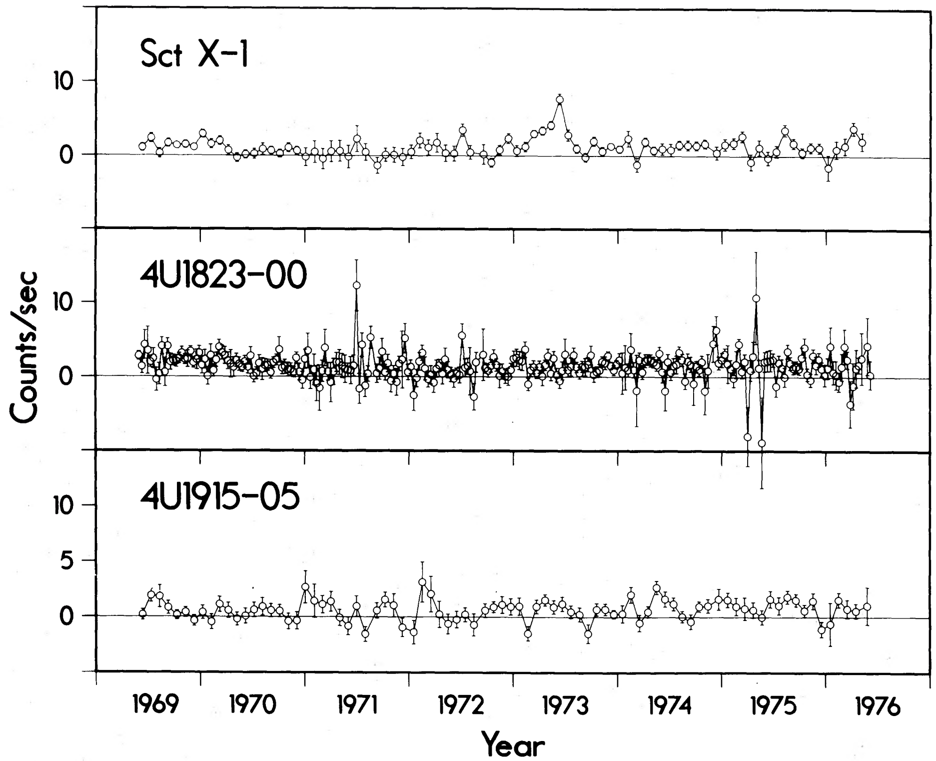

FIG. 2*a*

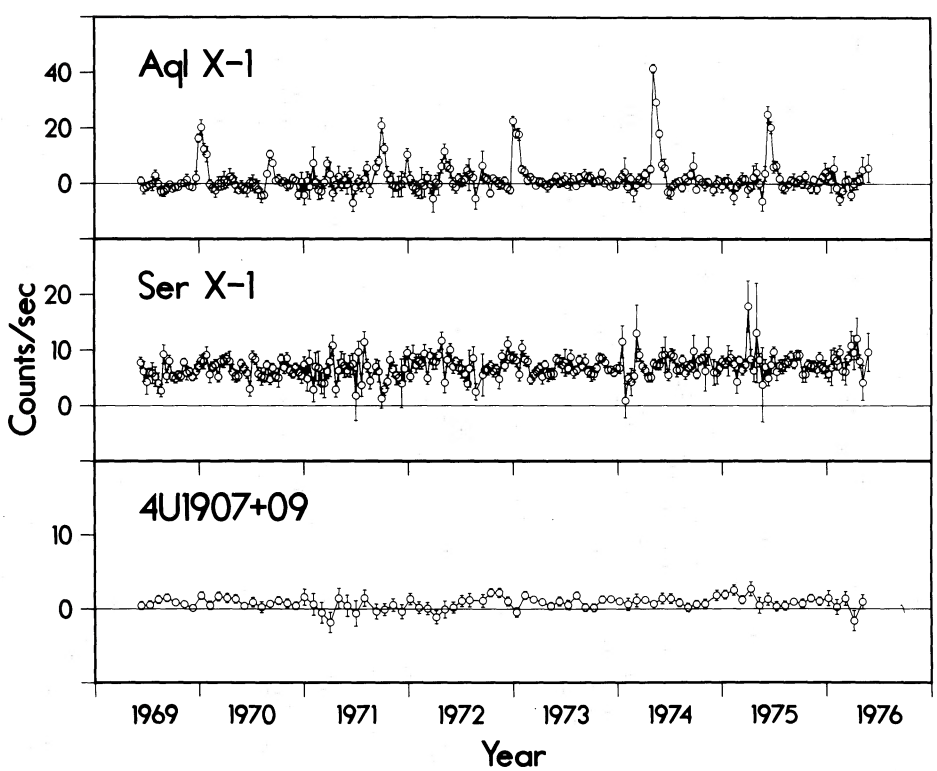

FIG. 2*b*

FIG. 2.—Time histories derived from the *Vela 5B* skymap data. Though the histories are calculated from 10 day maps, data from all but the brightest sources Aql X-1, Ser X-1, and 4U 1823–00 have been summed into 30 day bins for clarity of presentation. Er:or bars are statistical standard deviations.

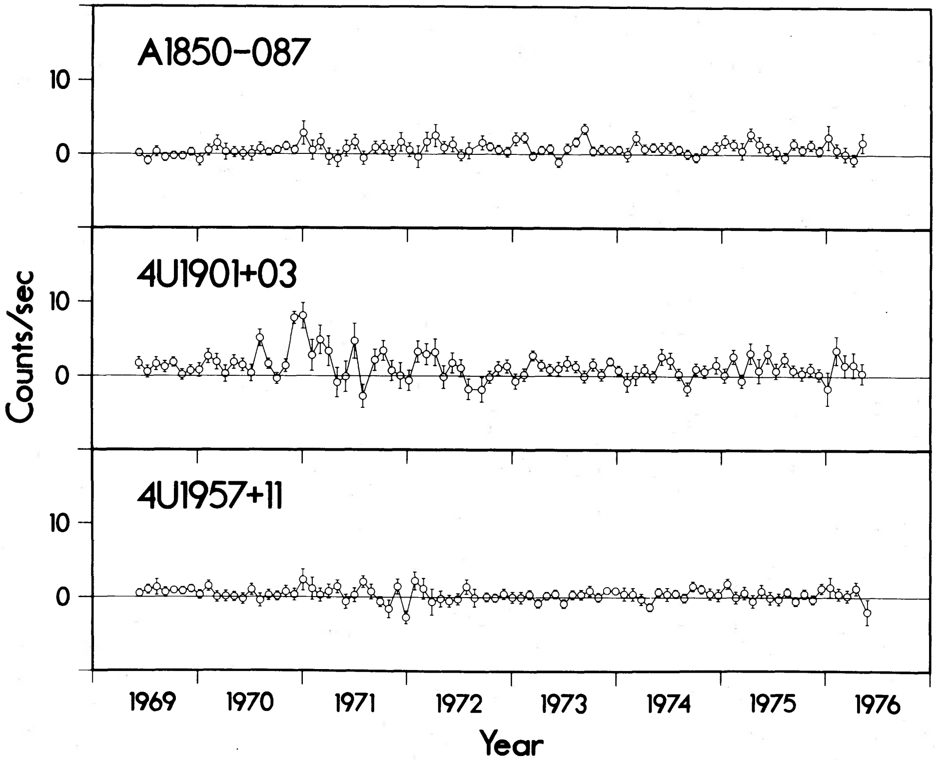

FIG. 2c

10% sinusoidal modulation of the flux observed by the *Ariel 5* Rotating Modulation Collimator experiment.

The source 4U 1907+09 has been identified with a heavily reddened OB star which shows Hα emission (Schwartz *et al.* 1980). *Ariel 5* Sky Survey Instrument observations from 1974 November to 1980 February showed a period of 8.380 ± 0.002 days, manifested by a modulation with nonzero minimum flux, which is interpreted as the orbital period (Marshall and Ricketts 1980). They interpret the system as a massive binary, similar to Vela X-1 or Cen X-3, in which mass transfer takes place via a stellar wind.

Both 4U 1901+03 and Sct X-1 are transient sources. Sct X-1 was discovered during a rocket flight on 1973 June 23 (Hill *et al.* 1974). It was found to have a heavily absorbed spectrum, and an intensity which corresponds to 15 *Uhuru* counts s^{-1} (UFU). It was observed by *Copernicus* during 1975 August–September, with an intensity consistent with the rocket observation (Charles, Mason, and Davison 1975). However, the source fell below the limit of the 4U catalog, implying a maximum flux at that epoch of 3 UFU (Forman *et al.* 1978). Sct X-1 is probably identified with the *Ariel 5* source A1829−06, which had a flux of 2–5 *Ariel* counts s^{-1} (~5–12 UFU; Seward *et al.* 1976). It was again observed at up to 12 μJy (~12 UFU) by the *HEAO* A-3 modulation collimator experiment in 1977–1978 (Reid *et al.* 1980). *HEAO* A-4 data shows significant transient activity in 1977 September, with an outburst duration (full width at half-maximum) of 12–14 days at 15–40 keV (Cooke *et al.* 1983). The source 4U 1901+03 was observed by *Uhuru* to undergo an outburst in 1971 (Forman, Jones, and Tananbaum 1976). It was observed at ~90 UFU at the end of 1970 December, but persisted at about a quarter of that level for at least 80 days. *Ariel 5* SSI data from 1974–1975 showed no evidence for the source, with an upper limit of 0.5 *Ariel* count s^{-1} ~ 1.5 UFU, clearly demonstrating transient behavior (Seward *et al.* 1976). No periodic behavior was previously known for either source.

III. TIME HISTORIES, FOURIER TRANSFORMS, AND DISCUSSION OF INDIVIDUAL SOURCES

Figure 2 shows the time histories derived from the *Vela* skymap data. Though the histories are calculated from 10 day maps, data have been summed into 30 day averages for clarity of plotting, with the exception of the bright sources Aql X-1, 4U 1823−00, and Ser X-1. The error bars plotted represent one standard deviation.

Fourier transforms of the time histories are shown in Figure 3. A secular trend was removed from each history by fitting and subtracting a cubic function; the residuals were weighted by their statistical errors before transformation. The transforms cover the frequency range up to the Nyquist frequency of 18.263 cycles $year^{-1}$. Fourier power is plotted in arbitrary units for each source. 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) Aql X-1

The 7 year time history of Aql X-1 shows seven prominent outbursts, in 1969 December–1970 January, 1970 August–September, 1971 September–November, 1972 April–May, 1973 January–February, 1974 April–June, and 1975 June–July. The source may be active at other times, with less statistical significance. Partial coverage of the 1971 and 1973 events was obtained by T. H. Markert (Ph.D. thesis, Massachusetts Institute of Technology, quoted by Kaluzienski *et al.* 1977). Extensive *Ariel 5* coverage of the 1975 outburst is reported by Kaluzienski *et al.* (1977). The other four events were observed

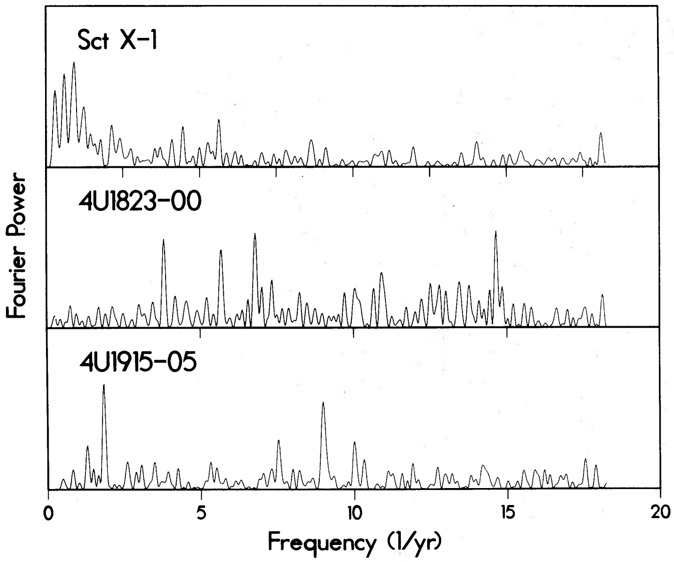

FIG. 3*a*

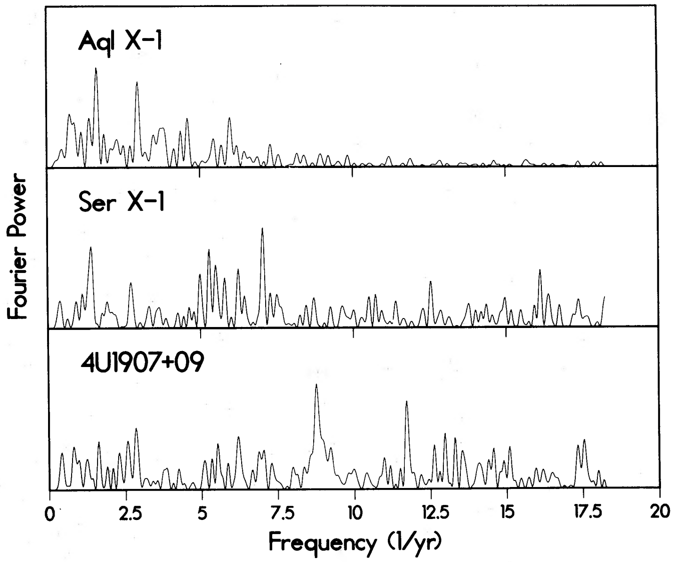

FIG. 3*b*

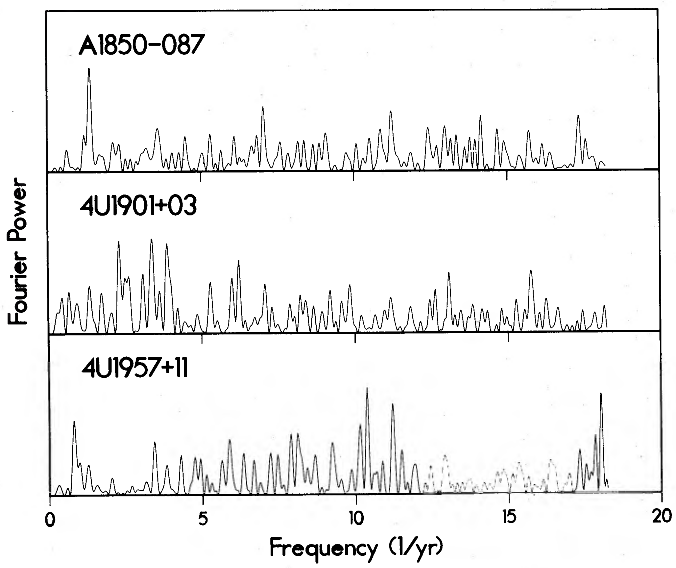

FIG. 3*c*

FIG. 3.—Direct Fourier transforms of the time histories, using 10 day averages only. Data points were weighted by their statistical errors before transformation.

only by *Vela*, though the 1974 outburst was surmised by Kaluzienski *et al.* (1977), and an optical counterpart of that outburst was detected in archival plate data by Thorstensen, Charles, and Bowyer (1978*b*). The *Uhuru* observation of activity in 1971 March (Cominsky *et al.* 1978) does not appear as a significant maximum in our data, but may be associated with a local maximum of 7.3 ± 2.3 counts s^{-1} during 1971 March 19–29. The seven outbursts from 1969 to 1975 have a mean separation of 436 ± 117 days (rms scatter). The mean *Vela* count rate for Aql X-1, averaged over the 7 year time history, is 1.6 counts s^{-1}. This rate corresponds to a mean luminosity of 3×10^{35} to 3×10^{36} ergs s^{-1} for a source distance of 2–6 kpc (Thorstensen, Charles, and Bowyer 1978*b*).

Time series analysis suggests an underlying cycle of 122–125 days for the eruptions of Aql X-1. The large scatter in the spacing of the major outbursts, visible in Figure 2*b*, indicates that they are not regular events. Fourier analysis (Fig. 3*b*) shows a broad spectrum of low-frequency power, including several peaks in the region 1–6 cycles per year. However, epoch-folding analysis clarifies the picture. Binned light curves are constructed at a number of frequencies, then tested for constancy via a χ^2 test. Figure 4 shows the results of this analysis, folding the data into ten bins over 400 frequencies from 0.15 to 5 cycles per year. The spectrum is dominated by $\nu = 2.98$ cycles per year and its subharmonics $\nu/2$, $\nu/3$, and $\nu/4$. There is a smaller peak at 2ν (not plotted). This analysis suggests an underlying period of approximately 122.6 days. It is clear from the time history that not every cycle of this candidate period is associated with an outburst; instead, the underlying cycle seems to be modulated by an irregular "enabling" function. Including post-1975 events (see below), the major outbursts are observed at separations of 2, 3, 2, 2, 4, 3, 3, and 6 times the fundamental cycle. Figure 5 shows the Aql X-1 time history, with arrows marking the maxima indicated by the epoch folding analysis. Though the cycle is striking, and lesser activity can be seen at some of the maxima not occupied by major events, there is a real jitter of the outburst events around predicted maxima.

The phase scatter is better seen in Figure 6, which plots as a function of 122.6 day phase the seven major *Vela* outbursts, and the 1976, 1977, 1978, and 1979 outbursts observed by *Ariel 5* (Kaluzienski *et al.* 1977; Holt and Kaluzienski 1977; Kaluzienski and Holt 1979; Charles *et al.* 1980). Available *Vela* data from the 1978 June outburst show a peak flux of ~1.3 Crab, in agreement with the light curve reported by Charles *et al.* (1980). The 1980 outburst observed by *Hakucho* is not plotted, as X-ray observations were taken only on the declining part of the light curve, so that the event onset is undefined (Koyama *et al.* 1981). Though a substantial phase jitter is evident, the 1976, 1978, and 1979 events seem to follow the pattern of the earlier *Vela* events, though the total 1970–1979 time span may best be fitted by a slightly longer period. The 1977 event is anomalous, as is the small 1971 March *Uhuru* maximum, both of which occur at phase ~0.6–0.7. The seven *Vela* events have a mean period time of

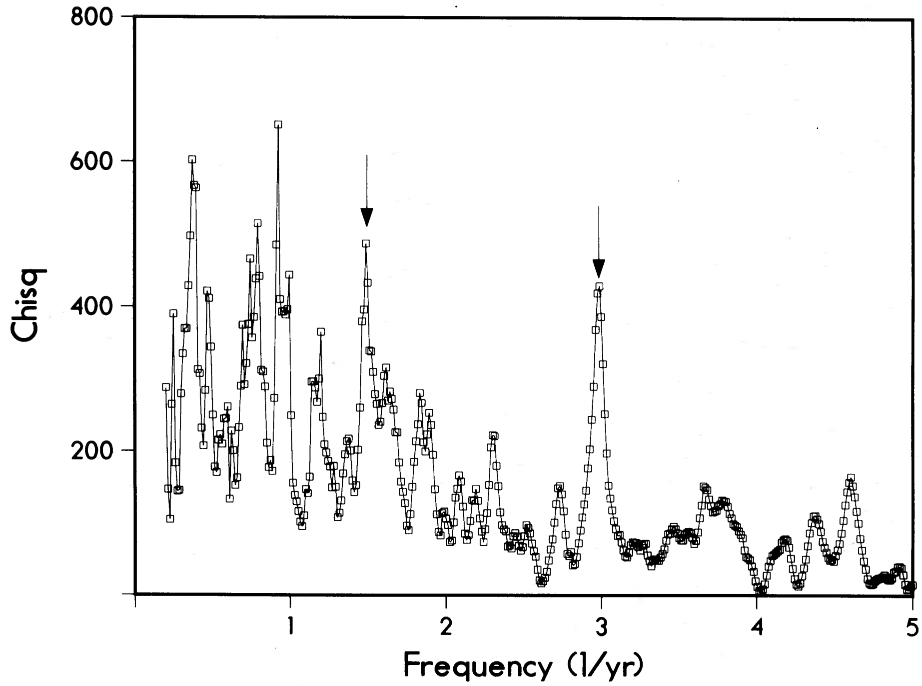

FIG. 4.—Epoch folding analysis of the Aql X-1 time history. The arrows denote 2.980 cycles per year (122.6 days) and its half harmonic.

124.2 days (first event to last event), with an rms drift of 9.5% in phase per cycle. Adding the 1976, 1978, and 1979 events observed by *Ariel 5*, we find a mean cycle of 124.9 days, with an rms phase drift of 8.3% per cycle. For this analysis, the time of each event is established by the half-maximum of the rise to outburst. The implied phase jitter can be compared to that observed in the 35 day cycle of Her X-1, for which Boynton, Crosa, and Deeter (1980) find an rms drift of 1.7% per cycle.

Two different analyses show that the 122–125 day cycle is not an artifact. The first involves the agreement in phase of discrete outbursts. For a given period, the probability that N events will agree in phase to the fraction of a cycle, x, is $(2x)^{(N-1)}$. For the seven *Vela* events, $x \sim 0.1$ (rms), while there are approximately 30 possible periods of $\nu \leq 5$ cycles per year that span the first and last events with an integer number of cycles. Because of the finite duration of the outbursts, a period of less than ~ 0.2 year would seem to be meaningless. The probability of the seven largest *Vela* events falling, by chance alignment, into phase agreement at least as good as that which we observe is less than 0.2%. The probability that three out of four ASM events follow the same pattern is 3.2%, for a joint probability of alignment of 6×10^{-5}. A second test of significance used a Monte Carlo technique and only the *Vela* data. The data set was randomly rearranged, by removing the seven major outbursts from the time history, and redistributing them with random spacings chosen to simulate the observed intervals between outbursts (mean spacing 436 days, standard deviation 117 days). The probability of a peak as significant as the 2.98 cycles per year peak occurring between 0 and 5 cycles per year was found to be less than 0.3%. By either estimate, the 122–125 day cycle is significant.

By analogy to Her X-1, the 122–125 day time scale may be a precession cycle, though it would need to be about 5 times as "noisy" in its phase jitter. The outbursts are most likely caused by an episode of enhanced accretion onto the compact object, rather than the variable aspect of a more constant source; this is demonstrated by the correlated optical activity, which shows that X-rays out of our line of sight, which are

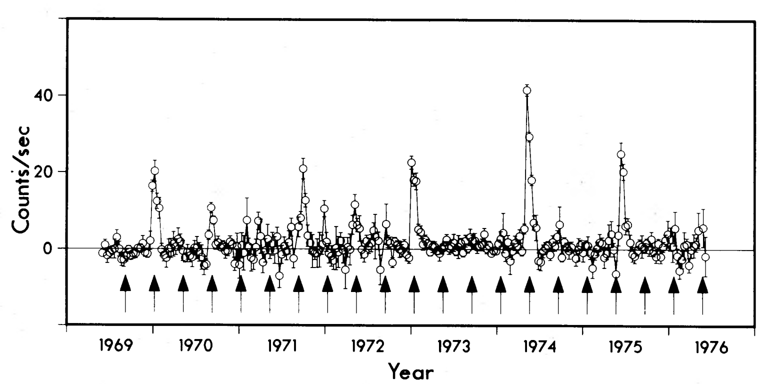

FIG. 5.—Time history of Aql X-1, with arrows marking the maxima predicted by epoch folding analysis. The epoch of maximum is JD 2,442,065, with frequency 2.980 cycles per year (P = 122.6 days).

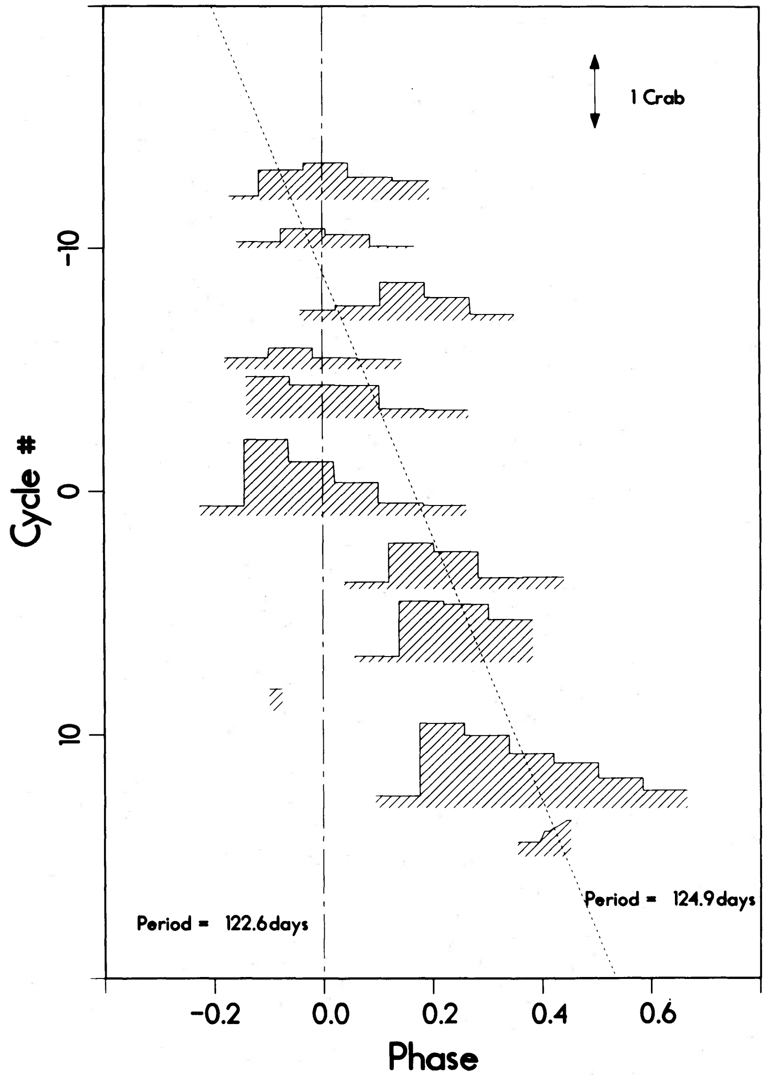

FIG. 6.—Eleven outbursts of Vela X-1, 1969–1979, plotted as a function of 122.6 day phase. Data are binned in 10 day sums, including the published *Ariel 5* ASM data for the events of 1976, 1977, 1978, and 1979 (see references in text). The period is a best fit period from the *Vela* epoch folding analysis; a slightly longer period of 124.9 days may be a better fit for the entire time span. The 1974 outburst corresponds to cycle 1.

reprocessed to yield the optical signal, occur simultaneously with the direct X-ray signal, and by the irregular nature of the 122–125 day cycle. Enhanced accretion onto the compact object may be the direct result of an enhancement of the mass transfer rate from the companion star to the accretion disk; in this case, it is difficult to explain why only a fraction of the cycles have outbursts. Alternatively, outbursts may be due to a disk instability, in which the accretion disk changes state and rapidly deposits matter on the central object, after reaching a critical density (Cannizzo, Wheeler, and Ghosh 1983; Faulkner 1983). For a periodically modulated accretion rate, it is likely that the critical density threshold would be exceeded, and an outburst commence, when the mass transfer rate to the disk is near maximum. The mass transfer rate could be modulated by intrinsic activity in the companion star, or perhaps be gated by the changing aspect of a precessing accretion disk (see Boynton, Crosa, and Deeter 1980). Precession of the companion star is an unlikely explanation for the disk precession, both because of the long time scale and because of the substantial phase noise in the cycle.

The expected time scale for a free disk precession in the Aql X-1 system is consistent with 122–125 days, if the accretion disk is about half the size of the Roche lobe about the X-ray source. If we assume that the precession is due to the free precession of a tilted disk, the precession period should scale approximately as the free precession period of a particle in orbit at the outer edge of the disk (Merritt and Petterson 1980). This period is:

$$P_{\rm edge} = \frac{8\pi}{3}\left(\frac{M_x}{G}\right)^{1/2}\frac{a^3}{M_c}\,r_d^{\,-3/2}\,(\cos\beta)^{-1}\,, \tag{1}$$

where M_x is the mass of the compact object, M_c is the mass of the companion, a is the orbital semimajor axis, r_d is the outer disk radius, and β is the angle between the disk edge and the orbital plane. We scale the disk radius to the radius of the Roche lobe around the compact object,

$$\rho = r_d/r_{\rm Roche}\,, \tag{2}$$

and assume the Roche radius approximation of Paczyński (1971),

$$r_{\rm Roche}/a = g(q) = [0.38 - 0.2 \log_{10}(q)] \quad \text{for} \quad 0.05 < q < 3 \,, \qquad (3a)$$

or

$$g(q) = 0.462(1 + q)^{-1/3} \quad \text{for} \quad q \geq 1.25 \,, \qquad (3b)$$

where the mass ratio q is M_c/M_x. Note that the fractional disk radius ρ cannot exceed 1. Assuming Kepler's law, the precession period should then scale as

$$P_{\rm disk} = A[(1 + q)^{1/2}/q]P_{\rm orb}[g(q)\rho]^{-3/2} \,, \qquad (4)$$

where the scaling coefficient A depends on the disk structure. We can therefore estimate the precession period for Aql X-1 by scaling from Her X-1. For Her X-1, q is 1.68, the orbital period $P_{\rm orb}$ equals 1.7 days, $\rho \approx 1$ (Gerand and Boynton 1976), and $P_{\rm disk} = 35$ days, yielding $A = 4.1$. Below, we assume $A \approx 4$ for determining possible disk precession periods for other systems. This scaling relation can be checked against the parameters of the LMC X-4 system. Interpreting the 30.5 day variation (Lang *et al.* 1981) as due to a precessing accretion disk, we find $A = 6.4\rho^{3/2}$, consistent with the value for Her X-1, given a slightly smaller accretion disk. For LMC X-4, we assume $P_{\rm orb} = 1.41$ days, $M_c = 25\ M_\odot$, and $M_x = 1.6\ M_\odot$ (Hutchings, Crampton, and Cowley 1978; Kelley *et al.* 1983). For Aql X-1, we may assume $P_{\rm orb} = 1.3$ days (Watson 1976), $M_x = 1.4\ M_\odot$, $M_c = 0.7\ M_\odot$ (assuming a K3 V companion, per Thorstensen, Charles, and Bowyer 1978*b*), and therefore $q = 0.5$. Using equation (4), we find that a 122–125 day period is plausible if $\rho \approx 0.5$. A similar value for ρ is necessary to yield a 294 day precession cycle for Cyg X-1 (Priedhorsky, Terrell, and Holt 1983). Noise in the 122–125 day cycle would be expected from variations in the diameter or mass distribution of the disk; these changes would certainly be expected to occur due to the violent disk variations caused by outbursts. For Her X-1, where the disk diameter may be limited by the Roche boundary, the disk configuration and therefore the precession timescale may tend to be more constant. Missing from this scenario is a physical model for the feedback mechanism by which the changing aspect of the disk modulates the accretion rate.

b) 4U 1915−05

The time history of 4U 1915−05 (Fig. 2*a*) shows long-term modulation, and the Fourier transform (Fig. 3*a*) shows two interesting maxima. The mean flux of 0.6 counts s^{-1} corresponds to a luminosity (3–12 keV) of $3 \times 10^{36}(d/10\ {\rm kpc})^2$ ergs s^{-1}, but there is considerable variability, including episodes of approximately zero flux. The mean rate corresponds to approximately 15 UFU for a source with the spectrum of the Crab, which is consistent with both the 4U catalog intensity (10–20 UFU; Forman *et al.* 1978) and the *OSO 8* and *HEAO* A-2 observations reported by White and Swank (1982). Peaks in the power spectrum at 1.839 ± 0.016 and 8.997 ± 0.024 cycles per year (198.6 and 40.6 days period) lie at 12.5 and 10.3 times the mean background power. The formal probabilities of random occurrence of the two peaks anywhere in the spectrum are 7×10^{-4} and 7×10^{-3}, respectively.

An additional test of significance of the two peaks was performed by a Monte Carlo technique. The time history was randomly reordered, then Fourier transformed 2000 times. A peak larger than the 1.839 $\rm yr^{-1}$ peak was observed somewhere in the spectrum 18 times; a peak larger than the 8.997 $\rm yr^{-1}$ peak was observed 116 times. These rates of random occurrence are consistent with the formal noise theory, given a mean background Fourier power which includes the power in the two peaks (the randomization process necessarily redistributes the Fourier power in the two main peaks randomly through the spectrum). The Monte Carlo technique therefore gives a conservative estimate of the significance of a Fourier peak. In any case, the 1.839 $\rm yr^{-1}$ periodicity is significant, with less than 1% probability of random occurrence anywhere in the spectrum. Measured against the mean background *outside* the two peaks, the 8.997 $\rm yr^{-1}$ peak is also significant. The width of the 1.839 cycles per year peak is consistent with a pure frequency, but the 8.997 cycles per year peak is significantly broadened.

The 199 day period is visible in the time history of Figure 2*a*. It is brought out more prominently in Figure 7, which plots *running* 30 day averages of the 10 day points. Arrows correspond to the minimum implied by the Fourier transform. It can be observed that each predicted minimum is indeed accompanied by a dip to approximately zero intensity in the count rate. The statistical significance of Figure 7 should not be overestimated, as successive points in the running average are, of course, not independent. The variation corresponds to a mean amplitude (of the best fit 199 day sinusoid) of 0.53 counts s^{-1} with minimum at JD 2,441,925.3. The 199 day cycle thus corresponds to an approximately 100% modulation of source intensity. The variation is therefore not aliased by the 10 day binning, as modulation at the lowest frequency which would alias to 1.839 (34.686 cycles per year = 10.53 days)

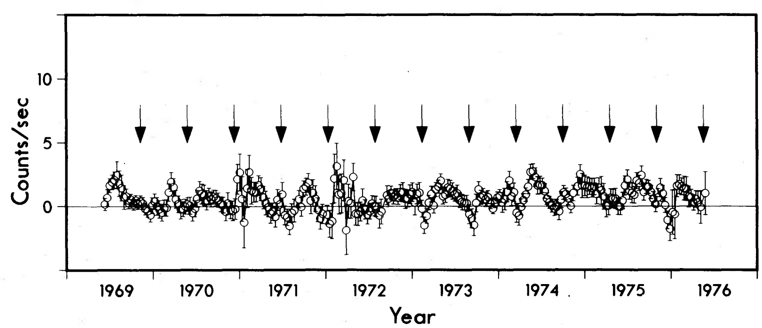

FIG. 7.—Running 30 day averages, plotted every 10 days, for 4U 1915−05. Arrows denote the minima predicted by the Fourier transform: epoch = JD 2,441,925, frequency = 1.839 per year, period = 198.6 days. The statistical significance of this plot should not be overestimated, as successive points in the running average are not independent.

would require an amplitude of 10 counts s^{-1} to yield the observed Fourier peak. This would imply a larger mean flux than is possible from the source. Figure 1 shows that there are no known nearby sources, even faint ones, that can contribute to this signal. Periods near the scan cycle of the *Vela* instrument may also be aliased to long periods; an intrinsic 2.230 or 2.354 day period could produce the 1.839 cycles per year peak in 4U 1915−05 (see Priedhorsky and Terrell 1983*a*). Such a coincidence with the scan rate is unlikely, and it is certain that a 100% modulation at about 2 days period would have been observed in the 7 days of *OSO 8* observations reported by White and Swank (1982). We therefore conclude that the 1.839 cycles per year peak corresponds to a real, long-term modulation in 4U 1915−05. Figure 8 shows the folded light curve, with error bars based on counting statistics only.

The nature of the 8.997 cycle per year (40.6 days) peak is less certain. We can again reject aliases, as the lowest frequency alias with the 10 day binning is 27.52 cycles per year (13.27 days), and would require a nonphysical modulation of 250%, while possible aliases with the scan period of 2.468 or 2.201 days would have been evident in the *OSO 8* data. The peak evidently corresponds to an ~80% sinusoidal modulation at 40.6 days period, but its relationship with the lower frequency peak is unclear. It differs from the fifth multiple of the 199 day frequency by approximately two standard deviations. Part of the power in this peak may represent fine structure in the 199 day light curve.

The presence of such long period variations is difficult to explain in the standard scenario of the X-ray bursters as low-mass, short-period (in this case, 50 minute!) binaries (Lewin and Joss 1981). The expected disk precession and orbital time scales for plausible parameters in the standard model are too short unless the companion has an extremely low mass. For example, if $M_x = 1.4\ M_\odot$ and $P_{\rm orb} = 50$ minutes, then $P_{\rm disk} = 199$ days for $M_c \approx 0.0015\rho^{-3/2}\ M_\odot$. The precession time scale of the low-mass companion is very short, and any tilt of its rotation axis would quickly be dissipated by tidal forces in such a close system.

One should consider the possibility that 4U 1915−05 is significantly different from the other X-ray bursters. Besides our result, two other observations set this source apart: (1) the hard spectrum observed both at quiescence and during the bursts, and (2) the 50 minute period. The 199 day period would be a reasonable precession time scale if 4U 1915−05 were instead associated with the G star (star 2 of Walter *et al.* 1982) which lies inside the HRI error circle. Walter *et al.* deduce a distance of 10–13 kpc for 4U 1915−05, based on the peak burst flux.

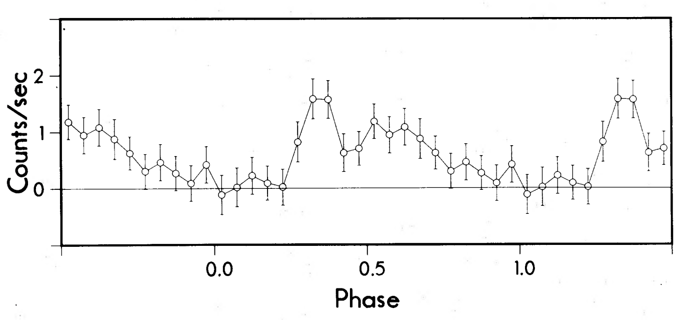

FIG. 8.—Light curve of 4U 1915−05 folded at a 198.6 day period. Errors are based on counting statistics only. Zero phase corresponds to JD 2,441,925 ± *nP*.

Star 2 has $V = 16.3$ mag (Grindlay 1981), which might correspond to a G giant of $M_V \approx 0$ at 10 kpc. We assume that the X-ray absorption of 3×10^{21} atoms cm^{-2} (White and Swank 1982) implies a visual extinction not much larger than 1 mag. If the G star is indeed the counterpart, the system may be similar to Cyg X-2 or the models of the bright galactic bulge sources proposed by Webbink, Rappaport, and Savonije (1983). Identification of the optical counterpart of 4U 1915−05 as a G giant is inconsistent with a 50 minute orbital period. Cyg X-2 is a system with an F giant counterpart, a 9.843 day period, and estimated component masses $M_x = 1.3$–$1.8\ M_\odot$ and $M_c = 0.5$–$1.1\ M_\odot$ (Cowley, Crampton, and Hutchings 1979). For these parameters, the estimated disk period scaled from equation (4) would be 300–$450\rho^{-3/2}$ days; for a lower mass G giant companion, with a shorter orbital period, the precession period could be consistent with the observed 199 days. For this scenario to be valid, the 50 minute variation of 4U 1915−05 must be explained as something other than an orbital period, perhaps the rotation or precession period of the neutron star.

c) Ser X-1

Our long-term observations of Ser X-1 shed little new light on its nature. The time history (Fig. 2*b*) shows no major variation at long time scales; the source does not stray far from its mean flux of 6.9 counts s^{-1} [L_x(3–12 keV) $\approx 3.5 \times 10^{37}(d/10\ {\rm kpc})^2$ ergs s^{-1}]. None of the Fourier peaks is significant. The period of 3.22–3.55 days proposed by Ponman (1981) would not be detectable with our present time resolution.

d) 4U 1907+09

The Fourier spectrum of 4U 1907+09 shows a broad peak at $P \sim 41.6$ days, with a suggestion of power at its first harmonic, which indicates a significant quasi periodicity. The probability that as much power would be found in four adjacent Fourier resolution elements, anywhere in the spectrum, as exists in the vicinity of 8.77 cycles per year is 1%; the probability of the excess at the first harmonic, given the candidate fundamental frequency, is 9%. Because the power is distributed over several Fourier elements, this peak is not significant when judged on the basis of peak amplitude alone. The frequency of the peak is 8.77 ± 0.16 cycles per year (41.6 ± 0.8 days), where we quote errors based on the peak FWHM (0.28 cycles per year), rather than the formal statistical error, because of the obvious frequency spread in the peak. Folded at 8.77 per year, the variation has an amplitude of 0.32 counts s^{-1}, yielding a modulated flux fraction of 35%. This amplitude is lower than the true cycle-to-cycle amplitude because of the frequency spread. The 8.77 per year period is not an alias of the 8.38 day period, reported by Marshall and Ricketts (1980), with the *Vela* scan period nor with the 10 day binning period.

The broadening of the Fourier peak suggests a "noisy" precession similar to that of Her X-1, but, because so little is known about the optical counterpart, it is not possible to state whether the period is a reasonable one for this system.

e) Sct X-1 and 4U 1901+03

The only prominent maxima observed for Sct X-1 and 4U 1901+03 are their discovery maxima, 1973 and 1970–1971, respectively. Hill *et al.* (1974) apparently did not observe Sct X-1 at its peak of 7.7 counts $s^{-1} \approx 200$ UFU (30 day average). The persistent emission observed by *Copernicus* and later experiments is evidenced by a mean flux after the 1973 peak (1974–1976) of 1.3 counts $s^{-1} \approx 30$ UFU. Conversion to UFU for this source is only approximate, as the hard, absorbed spectrum is detected more efficiently by the *Vela* 3–12 keV scintillation detector than in the 2–6 keV *Uhuru* channel.

Data for 4U 1901+03 show large error bars; this is the result of source confusion with Aql X-1 and Ser X-1 in the skymap fit. The persistent flux level 1972–1976 of 0.9 counts s^{-1} is not consistent with the *Uhuru* and *Ariel 5* upper limits and may be biased by source confusion.

f) 4U 1823−00

The Fourier spectrum of 4U 1823−00 has several peaks. None of them are individually significant, but there are too many large peaks to have appeared by chance, assuming a constant source. The three largest peaks fall at 3.823 ± 0.022, 6.802 ± 0.024, and 14.648 ± 0.020 cycles per year, respectively. As far as is known, 4U 1823−00 is in an uncrowded field; there are not several sources which could contribute separate periods to the time history. The cause of the structure in the transform is visible in Figure 2*a*, in the form of significant variability. Multiple Fourier peaks of this sort can be caused by intrinsic shot noise variability in the source, as in the short time scale variation of Cyg X-1 (Terrell 1972). The mean flux of 1.6 counts s^{-1} is consistent with the *Uhuru* value of 28–55 UFU. It will require further observations and analysis to determine the real nature of this object's variability.

g) A1850−087 and 4U 1957+11

The Fourier peak at 1.389 ± 0.022 cycles per year for A1850−087 is not significant; the random probability of a peak this large somewhere in the spectrum is $\sim 20\%$. None of the structure in the Fourier spectrum of 4U 1957+11 appears significant.

IV. CONCLUSION

We have presented the long-term time histories of nine galactic X-ray sources. Of these, Aql X-1 shows a 122–125 day time scale in its major eruptions. This is an underlying quasi periodicity; not every cycle is marked by an actual outburst. The magnitude of this time scale is consistent with a disk precession. The source 4U 1915−05 shows 199 day and perhaps 40.6 day periods. The 199 day period is too long to be explained as a precession in the standard low-mass binary model of this system, but is consistent with a precession if the optical counterpart is the prominent G star at the center of the *Einstein* HRI error box. The source 4U 1907+09 shows excess power in a resolved Fourier peak centered at 41.6 days period.

These results are based on an analysis with 10 day time resolution. We plan further work with finer resolution; the intrinsic *Vela* X-ray detector telemetry binning is 1 s. More rapid variations, such as the suspected 3.22–3.55 day period of Ser X-1, will then be accessible to study.

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