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NEW EVIDENCE ON THE NATURE OF THE NEUTRON STAR AND ACCRETION FLOW IN VELA X-1 FROM PULSE TIMING OBSERVATIONS

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ABSTRACT

We report Vela X-1 pulse timing results based on data spanning the period 1975–1982. After subtracting orbital effects, we were able to construct a power density spectrum of the residual fluctuations in the star's angular acceleration that covers 13 octaves in frequency, corresponding to periods from 0.25 to 2600 days. This spectrum is adequately fitted by a power law with exponent -0.04 ± 0.22, demonstrating that white noise in angular acceleration (second-order red noise in pulse phase or, equivalently, a random walk in pulse frequency) is an adequate description of the pulse timing fluctuations and the only acceptable simple noise model. The observed strength of the noise is $(6.4 \pm 2.0) \times 10^{-19}$ rad^2 s^{-3}. The *HEAO 1* observations reveal short-term angular accelerations as large as $\dot{\Omega}/\Omega = (5.8 \pm 1.4) \times 10^{-3}$ yr^{-1}. The sign of the acceleration reverses on time scales as short as the temporal resolution of the observations, which is 2 or 3 days. The change in the apparent secular trend of the pulse frequency from spin-up to spin-down in 1979 and the frequency variations observed on much shorter time scales are consistent with the same random noise process. We mention several of the important constraints on the properties of the neutron star and the temporal and velocity structure of the accretion flow implied by our results.

Subject headings: stars: binaries — stars: magnetic — stars: neutron — stars: rotation — X-rays: binaries — X-rays: sources

I. INTRODUCTION

Variations in the intrinsic pulse frequencies of neutron star X-ray sources are believed to reflect changes in the rotation rate of the stellar crust produced by torques originating outside and inside the star. The external torque depends on the flow pattern of the accreting plasma, whereas the internal torque depends on the state of the interior and its coupling to the crust. Thus, the study of intrinsic frequency variations can provide information both about the accretion flow and the star itself.

Analysis of the statistical properties of such variations has proved to be a particularly fruitful approach. Three years after the discovery of the Crab pulsar, Boynton *et al.* (1972; see also Groth 1975 and Cordes 1980) showed that its small-scale pulse frequency variations can be described adequately as a random noise process. Soon afterward, Lamb, Pines, and Shaham (1974, 1976) argued on theoretical grounds that the pulse frequency variations seen in many pulsing X-ray stars are due to fluctuations in the neutron star rotation rate and should be amenable to a description in terms of simple (integer power-law) noise processes. They showed that the limited data then available for Her X-1 and Cen X-3 were consistent with this conjecture. Lamb (1977) showed that, regardless of its cause, noise in the rotation rate can be used to probe the internal properties of the pulsing star. These ideas were subsequently worked out in detail by Lamb, Pines, and Shaham (1978*a*, *b*). Lamb (1979) and Ghosh and Lamb (1979) showed how variations in the pulse frequency could be used to study accretion flow patterns. Motivated by this work, Boynton and Deeter (1979), Boynton (1981), and Deeter (1981) were able to place stringent constraints on models of the internal structure of the Crab pulsar and Her X-1. In the case of the Crab, they specifically ruled out the two-component model proposed by Baym *et al.* (1969) to explain macroglitch behavior in pulsars.

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In this *Letter* we summarize the results of a detailed study of the 283 s pulsing X-ray star Vela X-1 using pulse timing techniques. We find that the frequency variations in this source are consistent with the occurrence of a succession of temporally unresolved events that can be characterized mathematically as second-order red noise in the pulse phase (random walk in pulse frequency). The data on which this conclusion is based span the period 1975–1982 and were obtained from a special series of *HEAO 1* and *SAS 3* observations made during 1978 November and 1979 January, from previous observations made with *OSO 8*, and from other, published observations. Details of the observations and the analysis as well as a full discussion of the results will be published elsewhere.

II. OBSERVATIONS, METHOD, AND RESULTS

Observations.—New data for this study were obtained in a series of *HEAO* A-1 and A-2 and *SAS 3* observations made specifically for this purpose, and from previously recorded *OSO 8* observations. The *OSO 8* observations provided continuous coverage of a 36 day interval from 1978 May 9 to June 14 while the *HEAO 1* observations sparsely sampled the 60 day interval from 1978 November 1 to December 30. The *SAS 3* observations provided continuous coverage of a 4 day interval from 1979 January 15 to January 19. The 12 half-day *HEAO 1* observations were deliberately spaced at intervals of 1.5, 3, 6, 12, and 24 days, in order to sample source behavior over a predetermined range of time scales. In addition to these new data, we also used data from the literature, including recent *Hakucho* observations (Nagase *et al.* 1984).

Method of analysis.—In order to study the behavior of the intrinsic pulse frequency of the neutron star, the variation caused by the motion of the star about its binary companion must first be removed. This is a complication, because the parameters of the orbit are best determined by pulse timing and hence are affected by the noise in the rotation that we seek to study. In fact, in Vela X-1 this noise dominates the uncertainty in the orbital parameters. Thus, an understanding of the properties of the noise is essential to a correct estimation of the orbital uncertainty. In our solutions, the effect of this noise on the orbital parameters was treated explicitly.

We solved for the local orbits and pulse phase behavior in 1978 May and 1978 December by using a modified version of the approach described by Epstein (1977), in which time, in the frame of the source, is taken as the independent variable and pulse phase, as the dependent variable. The measured pulse phases showed significantly greater point-to-point scatter than expected from photon statistics, due to additional short-term fluctuations in the pulse shape (the high-quality *HEAO 1* data, for example, showed an rms scatter more than 5 times that expected from photon statistics alone). The lowest harmonics of the pulse shape were found to be the most variable. The variance in the pulse phases derived from the highest quality data was reduced by as much as a factor of 4 by applying an optimum filter to the pulse templates prior to the timing analysis. Typical final uncertainties, expressed as equivalent rms residual arrival times, ranged from 0.50 s for the *HEAO 1* data to 1.32 s for the *OSO 8* data. We made no attempt to combine the 1978 May and 1978 November–1979 January data sets using a common pulse ephemeris, since the observed pulse frequency fluctuations preclude pulse numbering over such a large gap. Instead, the best fit orbital parameters for each of these two data sets were determined separately using the method of least squares.

Standard orbit and pulse frequency.—In order to obtain as precise an orbit as possible, we combined our two solutions with three that had been published previously (Rappaport, Joss, and McClintock 1977; Rappaport, Joss, and Stothers 1980; Hayakawa 1981). These particular three solutions were chosen because each is based on a block of data short enough to be covered by a single pulse ephemeris. Using the approach outlined by Deeter (1984), we were able to estimate the *total uncertainty* in each orbital parameter (from all sources of noise) for each of these solutions. The presence of the random walk increases the uncertainty in the local orbital epoch and the semimajor axis by factors of 10 and 5, respectively, for the *HEAO 1* data. All five orbits were then averaged, using appropriate relative weights. The result, which we call the "standard orbit," is given in Table 1. This orbit is the first reported for Vela X-1 that includes an assessment of the uncertainty introduced by the presence of red noise in the rotation of the neutron star. Even so, the uncertainties listed here are smaller than those quoted in previous works because of the large quantity of high count-rate data available to us. We found no evidence for a significant change in the orbital period.

Final pulse phases were obtained by employing the standard orbit given in Table 1. We then constructed the time history of the pulse frequency from local straight line fits to the pulse phases. All the currently available pulse frequency estimates, including those based on previously published data, are shown in Figure 1. The *HEAO 1* observations reveal short term angular accelerations of both signs and as large as $\dot{\Omega}/\Omega = 6 \times 10^{-3}$ yr^{-1}. The sign of the acceleration sometimes reverses on time scales as short as the temporal resolution of the observations, which was 2 or 3 days.

Power density spectrum.—We computed the power density spectrum of the intrinsic fluctuations in angular acceleration,

TABLE 1

MEAN ORBITAL PARAMETERS FOR VELA X-1

Parameter[a]	Value [b]
E_0 (HJD)	2,443,821.8604 ± 0.0056
$P_{\rm orb}$ (day)	8.96443 ± 0.00022
$(a/c)\sin i$ (s) ...	112.70 ± 0.47
e	0.0881 ± 0.0036
ω (deg)	152.8 ± 2.2[c]
$\dot{\omega}$ (deg yr^{-1}) ...	+6.9 ± 3.4
$f(M)$ $(M_\odot)$	19.12 ± 0.24

[a] E_0 is the orbital epoch, defined as the time when the mean longitude equals 90°. All other symbols have their usual meanings. For a discussion of this choice of orbital parameters, see Deeter, Boynton, and Pravdo 1981.

[b] Uncertainties are 1 σ. In terms of their uncertainties, the parameters given by Rappaport, Joss, and Stothers 1980 and Nagase *et al.* 1984 are consistent with those reported here. In terms of the uncertainties given here, some parameters in these previous orbits are discrepant by as much as 9 σ.

[c] At the epoch E_0.

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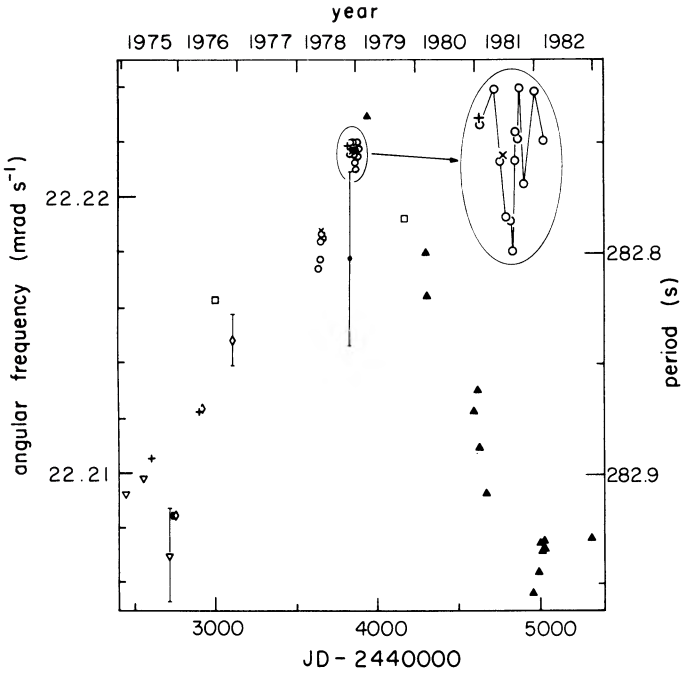

FIG. 1.—Long-term history of the angular frequency of Vela X-1. The pulse period in seconds is also given on the scale at the right, increasing downward. Open inverted triangles are data taken with *Copernicus* and *Ariel 5* (Charles *et al.* 1978); crosses, *SAS 3* (Rappaport, Joss, and McClintock 1976; Rappaport and Joss 1977; Rappaport, Joss, and Stothers 1980); open squares, *COS B* (Ögelman *et al.* 1977; Molteni *et al.* 1982); open diamonds, other *OSO 8* data (Becker *et al.* 1978); open circles, present work; diagonal crosses, other *HEAO 1* data (Bautz *et al.* 1983); filled circle, balloon flight (Staubert *et al.* 1980); filled upright triangles, *Hakucho* (Nagase *et al.* 1984). Vertical bars represent 1 σ confidence intervals and are only shown where they are significantly larger than the symbols. The large oval shows the *HEAO 1* results expanded vertically and horizontally by a factor of 6. *Hakucho* results are plotted at the center of observing intervals.

following the method described by Deeter (1984; see also Deeter and Boynton 1982). The resulting spectrum covers 13 octaves in frequency and is shown in Figure 2.

The spectrum is adequately fitted (χ^2 of 4.9 for 5 d.o.f.) for periods from 5 to 2600 days by a straight line with a slope of -0.04 ± 0.22, showing that white noise in angular acceleration (second-order red noise in pulse phase or, equivalently, a random walk in pulse frequency) is an adequate description of the intrinsic pulse frequency fluctuations and the only acceptable simple noise model. As is evident in Figure 2, the spectrum at periods shorter than 5 days is dominated by measurement noise and hence was not included in the fit. The average power density is $(6.4 \pm 2.0) \times 10^{-19}$ rad^2 s^{-4} Hz^{-1}, which is equivalent to a noise strength $S = R\langle \delta\Omega^2 \rangle$ of 6.4×10^{-19} rad^2 s^{-3}.

The independent measurements of the spectrum at periods shorter than 30 days derived from the 1978 May and 1978 December data are not significantly different; furthermore, both high-frequency spectra are consistent with the spectrum at periods longer than 30 days. We also tested (1) whether the noise strength changed significantly when the apparent secular trend changed from spin-up to spin-down in 1979 and (2) whether the power density at the lowest frequency sampled, which is most sensitive to the change in pulse frequency over the full 2600 day span of the data, is different from that at higher frequencies. According to these statistical tests, the noise strength after 1979 March is not significantly different from that before this date nor is the power density at $P = 2600$ days significantly different from that at shorter periods. Thus, on the basis of the present data *the change in the apparent secular trend of the pulse frequency from spin-up to spin-down in 1979 and the frequency variations observed on much shorter time scales are consistent with the same random noise process*. We note that simulated random walks (see, for example, the panel labeled "phase noise" in Fig. 1 of Cordes 1980) show "secular" behavior very similar to that of the Vela X-1 frequency record.

III. DISCUSSION AND CONCLUSIONS

Noise in the rotation of pulsing X-ray sources can arise either from processes inside the neutron star or from fluctuations in the external accretion torque (see Lamb 1982). Whatever their origin, the events in Vela X-1 last less than about 10 days; otherwise, the power spectrum would drop significantly near $\tau = 10$ days. There is no evidence for any significant change in the properties of the noise during the period 1975–1982.

The absence of any features in the noise spectrum of Vela X-1 means that the neutron star is responding like a rigid body on the time scales that we have explored. This conclusion can be made quantitative by comparing the predictions of particular models with the observed power spectrum (see Boynton 1981). Suppose, for instance, that the neutron star

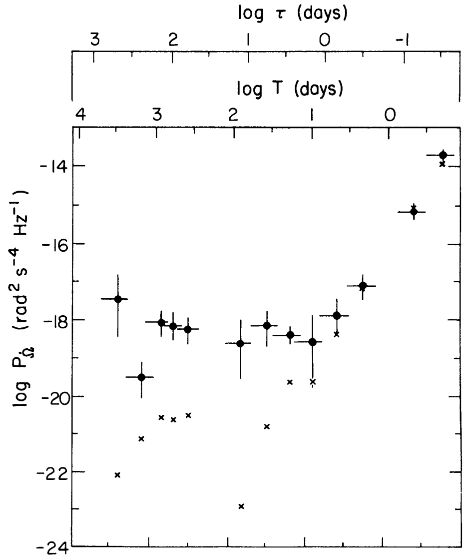

FIG. 2.—Power density of fluctuations in angular acceleration as a function of circular frequency f (*bottom axis*). A sinusoidal variation with frequency f would produce a feature at period $T = 1/f$ (*lower top axis*), whereas a fluctuation with e-folding time τ (*upper top axis*) would produce a feature at period $T = 2\pi\tau$. The vertical bar on each power density estimate represents the 1 σ confidence interval, based on the effective number of independent estimates contained therein, while the horizontal bar represents the point equivalent to 1 σ on the frequency response of each estimator. The crosses indicate the noise contributed by measurement errors, which are largely due to variations in the pulse shape.

consists of a crust weakly coupled to a superfluid component. If the intrinsic rotation noise arises from events in the crust or from external torques, there will be a step in the power spectrum near the coupling time scale. Limits on the size of such a step in the observed spectrum allow us to reject with 99% confidence models in which the superfluid component has a moment of inertia larger than 6 times that of the crust, if the crust-superfluid coupling time is in the range 1–30 days. For larger superfluid components, we can reject models with even shorter coupling time scales. For internal torques, such as might arise from vortex unpinning (Alpar *et al.* 1984), we can state with 99% confidence that the relaxation time is greater than 50 days. Other arguments that make vortex unpinning appear unlikely as the source of the noise will be described elsewhere.

Our observations also restrict models of the accretion torque. The short-term angular accelerations reported here are some 70 times larger than expected for accretion from a uniform wind, assuming a wind velocity of 860 km s^{-1} (Dupree *et al.* 1980) and an orbital velocity of 300 km s^{-1}. The indicated circulation is so large that the flow may form a ring or disk around the magnetosphere of the neutron star. Furthermore, the acceleration sometimes has a sign opposite to that expected for accretion from a uniform wind. The observed reversals in the sign of the angular acceleration within 2 or 3 days imply corresponding reversals in the sign of the accretion torque.

To summarize, our results (1) suggest that the pulse frequency variations seen during 1975–1982 are due to a series of unresolved events that can be characterized mathematically as second-order red noise in pulse phase; (2) indicate that there was no change in the behavior of the system in 1979 March; and (3) place severe constraints on models of the accretion flow and the internal structure of the neutron star in this system.

It is a pleasure to thank the *OSO 8* group and especially P. Serlemitsos for providing unpublished *OSO 8* data for use in this study. We also thank the *SAS 3* group and especially H. Bradt for arranging the special 1979 January *SAS 3* observation and for assembling the data from this observation. Finally, we thank D. Pakey for help in assembling the *HEAO* A-1 data and D. Percival for assistance in the early stages of the data analysis. This research was supported in part by NSF grants AST 80-01471 and AST 82-16661 (at Washington) and PHY 78-04404 and PHY 80-25605 (at Illinois), and by NASA grants NAS 8-33360 (at Washington) and NSG 7653 (at Illinois). Part of the research described in this work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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