THE HEAO-1 NEUTRON STAR TIMING EXPERIMENT

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INTRODUCTION

I have been asked to describe the HEAO-1 neutron star timing experiment, even though the analysis and interpretation of this experiment are still in progress. The investigators who are participating in this experiment with me are Paul Boynton and John Deeter at the University of Washington, Steve Pravdo and Nick White at Goddard Space Flight Center, and Kent Wood at the Naval Research Laboratory. In this progress report I will describe briefly the scientific motivation for the experiment, the reasons for our choice of Her X-1 and Vela X-1 as promising sources to study, our methodology, and the current status of the experiment.

SCIENTIFIC MOTIVATION

The basic scientific goals of the experiment are summarized in Table 1. There are two basic thrusts: first, to improve our understanding of the internal structure of neutron stars, and second, to obtain more information about accretion flows. The way that we hope to address both questions is to study in detail the changes in the pulsation periods of Her X-1 and Vela X-1. These changes are thought to be due to changes in the angular momentum, and hence the rotation period, of the neutron star crust. According to current ideas, the change in period over a sufficiently long time is due to the action of the external accretion torque (Pringle and Rees 1972; Lamb, Pethick, and Pines 1973), while period fluctuations on shorter time scales may be caused by fluctuations in either the external accretion torque (Elsner and Lamb 1976) or the internal torque exerted on the crust by the superfluid neutron liquid interior (Lamb, Pines, and Shaham 1978). Some possible sources of internal and external torque fluctuations are listed in Table 2.

The external torque depends on the flow pattern of the accreting plasma, while the internal torque depends on the strength and nature of the coupling between the liquid interior and the crust. The response of the neutron star to a torque acting on the crust, whether external or internal, depends on the dynamical properties of the star: the "applied signal" represented by the torque is, in effect, "filtered" by the coupled crust-superfluid system to produce an "output" represented by changes in the pulsation period. Thus, a detailed study of period changes in a given X-ray source can provide information both about the properties of the accretion flow onto the star and about the properties of the star itself.

In the following subsections I first describe why measurement of short-term fluctuations in the pulse phase and X-ray flux is the most promising approach to use in such studies. I then outline how one can extract information about the internal structure and dynamical properties of the neutron star from such measurements and describe briefly how they can also be used to determine the accretion flow pattern and to test accretion theories.

Advantages of Studying Short-Term Behavior

The interpretation of any particular period change is complicated by the fact that the response of the neutron star interior is not known a priori. Hence, such a change might be due either to the internal and external torques acting at the time, or to the response of the star to previous values of these torques. If the change in the rotation rate were smooth and the total observing interval were long, the likelihood that the star was still responding to an earlier value of the torque would be less, but the interpretation would still be ambiguous. In fact, the period changes in those sources that have been studied carefully are observed to be highly irregular.

Recently, Lamb, Pines, and Shaham (1978) pointed out that if the torque fluctuations that cause the short-term period variations can be described by a simple noise process, then these interpretational difficulties can be overcome by using the period variations themselves to determine the dynamical response of the neutron star. These authors further suggested that either white or red torque fluctuations are physically plausible models and showed that the available data on Her X-1 and Cen X-3 are consistent with either type of torque noise. Motivated by these studies, Boynton and Deeter (1979) used the Uhuru data on Her X-1 to compute the power density spectrum of the pulse phase fluctuations in this source. They find that the torque fluctuations in Her X-1 are describable as white noise over a wide range of frequencies and derive significant constraints on the dynamical response of the neutron star from their analysis. Thus, this method of determining the neutron star response appears quite promising. Use of this method requires a dense, regular sequence of pulse phase measurements.

Measurements of the short-term behavior of the pulse phase and X-ray flux also provide the best type of data for determining the accretion flow pattern and the large-scale structure of the magnetosphere (see Ghosh and Lamb 1979b). First, accretion theory predicts that the change in spin period between two observations depends sensitively on the behavior of the accretion luminosity L during the interval. If L is highly variable, as it often is, spot checks at widely-spaced times may lead to very large errors in the inferred luminosity history L(t). Such errors can be minimized by measuring the period and flux at frequent intervals. Second, theoretical models necessarily include a number of adjustable parameters, such as the mass, radius, effective moment of inertia, and magnetic dipole moment of the star. Although the dependence on these parameters does not permit one to fit every possible value of P, $\dot{P}$, and L, in practice the possibility of adjusting these parameters introduces a substantial degree of freedom. If only the average values of $\dot{P}$ and L are known, there is often not enough information to test the theory. However, once these parameters are determined there is no more freedom, so that additional measurements of P, $\dot{P}$, and L provide a quantitative test of the theory. Finally, since the effective inertial moment of the star generally is not constant, one must combine the theoretical equation for the accretion torque as a function of the mass accretion rate with the observed luminosity behavior L(t) and a dynamical model of the neutron star crust and core in order to solve for the predicted period behavior P(t) of the neutron star crust. Only then can a comparison be made with the observed period behavior. This procedure can only be carried out if a dense, regular sequence of period and flux measurements is available.

In summary, only frequent, regular measurements of the pulse phase and flux of neutron star X-ray sources can provide the type of data required to confront current theoretical models of their magnetospheres and interiors.

Probing Neutron Star Interiors

The actual response of a neutron star to fluctuating torques acting on its crust is expected to be quite complex. A key question is the coupling time between the solid crust and the rest of the star, which then determines the effective inertial moment involved in angular momentum changes on various time scales. X-ray timing observations of pulsating sources can measure, or at least severely constrain, the moment of inertia, I_c, of that part of the star which responds quickly to torque variations; the moment of inertia, I_s, of that part which responds only more slowly; and the coupling time, τ, between them. Such measurements can be made by observing the fluctuation of the angular velocity of the crust and then computing the power density spectrum of the fluctuation. If the spectrum obeys a power law at both high and low frequencies, a description of the torque fluctuations in terms of a simple noise model is possible; the index of the power law then indicates the dominant type of noise. The power law region of the spectrum is expected to extend over many decades in frequency, and defines the range of time scales and frequencies that can be searched for evidence of the crust-core coupling time τ and the frequencies of any internal modes.

In the absence of an internal mode with a frequency within the range covered by the power spectrum analysis, the two-component model predicts a shoulder in the power spectrum at $\omega \sim 1/\tau$, with the power at higher frequencies enhanced by the factor $(I/I_c)^2$, where $I = I_s + I_c$ is the total moment of inertia of the star. This is because the lower frequency torque fluctuations drive both the crust and superfluid whereas the higher frequency fluctuations drive only the crust. An example of this type of power spectrum is shown in Figure 1a, which displays the response of a two-component neutron star to white torque noise.

The ratio of inertial moments, I/I_c, is a sensitive function of the mass of the neutron star and the equation of state, ranging from 1 for the lightest neutron stars and the stiffest equations of state to greater than 100 for the maximum mass neutron stars given by soft equations of state. Thus the shoulder in the power spectrum at $\omega \sim 1/\tau$, which is proportional to $(I/I_c)^2$, may be quite prominent. The detection of such a shoulder would provide the first evidence for the existence of superfluid neutrons in X-ray sources. It would also help to pin down the correct equation of state of matter at very high densities, and to stimulate further theoretical work on the nature of the coupling between crust and core (see Lamb 1977 and references therein).

In the presence of an internal mode of frequency ω_o, the generalized two-component model predicts a peak in the power spectrum at $\omega = \omega_o$ with a width $\Delta\omega \sim 1/\tau$, where τ is the relaxation time of the mode. Such a spectrum is shown in Figure 1b for the case of a lightly damped mode ($\omega_o\tau >> 1$) excited by white torque noise. The spectrum shows a sharp notch in the spectrum at $\omega = (I_c/I)^{1/2}\omega_o$, as well as the enhancement of the power at higher frequencies already seen in Figure 1a. Detection of internal resonant modes would allow a direct comparison with theoretical work on the dynamics of the degenerate electron-proton plasma and the superfluid neutron liquid (see Lamb 1979 and references therein), and would provide an important stimulus to this work.

Probing Accretion Flows

As noted earlier, one possible explanation for a fluctuating neutron star spin rate is the presence of fluctuations in the mass accretion rate, which will produce correlated changes in the pulse period and X-ray flux. Clearly, however, the extraction of information concerning the accretion flow from observations of period fluctuations requires some care. First, in order to study the accretion flow in this way the period fluctuations must be shown to be due to fluctuations in the accretion torque rather than the internal torques. Second, the response of the neutron star must be considered in interpreting the data, since the response time of the liquid interior may be comparable to the time scale for changes in the accretion torque.

Accretion torque fluctuations can potentially be identified by searching for correlated changes in the pulse period P and the X-ray flux F at earth, since accretion theory predicts that fluctuations in the mass accretion rate will cause fluctuations in both the accretion luminosity and the accretion torque; correlated changes in P and F are much less likely if the period change is caused by internal torque fluctuations. Fluctuations in the accretion rate appear quite natural and can easily produce torque variations large enough to account for the period wandering observed in the well-studied pulsating sources (Lamb, Pines, and Shaham 1978; Ghosh and Lamb 1979b). I shall therefore focus on torque variations that arise in this way.

To the extent that the torque variations can be described by a simple noise process, one can disentangle the variations in the torque from the time-dependent response of the star in the manner described above. Once this is accomplished, a sequence of pulse period and X-ray flux measurements can potentially be used to (1) determine whether the source is fed by a Keplerian accretion disk or by some other accretion flow pattern, (2) test quantitatively the theory of disk accretion, (3) confirm that the X-ray source is indeed a neutron star, (4) determine accurately the dipole moment of the X-ray star, and (5) establish the nature of the accretion torque fluctuations.

The first step in achieving these goals is to construct a theoretical relation between the X-ray flux F(t) at earth and the pulse period P(t). Such a relation can be constructed if one has available (1) a relation between F and the accretion luminosity L, (2) a relation between L and the mass accretion rate $\dot{M}$, (3) a relation between $\dot{M}$ and the torque N, and (4) a model for the change in the rotation of the neutron star crust caused by N. Assuming that the X-ray flux at earth accurately reflects the X-ray luminosity and that the latter is essentially the accretion luminosity L, then $F = L/4\pi D^2$, where D is the distance to the source, while $L = \dot{M}(GM/R)$. One can then turn to accretion theory for a relation between $\dot{M}$ and N. Finally, the stellar properties required to determine the change in the rotation period P of the neutron star crust produced by the torque N are fixed by the power density spectrum of pulse phase fluctuations.

Once a theoretical relation between F(t) and P(t) has been constructed, it can be tested by comparison with a sequence of X-ray flux and pulse period measurements. As an example of how this approach can be applied, consider the case of disk accretion, for which a quantitative theory has recently been developed (Ghosh and Lamb 1978, 1979a,b). Figure 2 shows the dependence of the accretion torque on the mass accretion rate which is predicted by this model. The dashed curve shows the torque that would occur if the transition zone between the disk and the magnetosphere were narrow, whereas the solid curve shows the torque given by the broad transition zone predicted by the theory. This illustrates how measurements of the accretion torque can furnish information about the accretion flow. If the neutron star responds like a rigid body with a constant effective moment of inertia I_{eff}, then this torque curve predicts that for a star of given mass and magnetic moment, $\dot{P}$ is a function only of $PL^{3/7}$. The character of this relation is shown in Figure 3. For large values of $PL^{3/7}$, the star is a slow rotator and $-\dot{P}$ scales as $(PL^{3/7})^2$. Thus, if log $(-\dot{P})$ is plotted versus log $(PL^{3/7})$, the theoretical spin-up curve is a straight line of slope 2 in the region of slow rotation. As $PL^{3/7}$ decreases, the fastness ω_s increases and log $(-\dot{P})$ falls below the extrapolation of this line. Finally, at the value of $PL^{3/7}$ for which ω_s reaches a certain critical value, $\dot{P}$ vanishes and log $(-\dot{P})$ diverges. The value of $PL^{3/7}$ at which the spin-up curve begins to fall below the extrapolated straight line depends sensitively on the magnetic moment of the star, as shown.

If observed values of P, $\dot{P}$, and L are plotted on such a graph and are qualitatively represented by the theoretical curve, this would constitute strong evidence that the X-ray source is a neutron star which is disk-fed. The shape of the curve would then give the size of the dipole magnetic moment, while a detailed comparison of the data with the theoretical curve would provide a quantitative test of the theory. Finally, a detailed comparison of the time history of the pulse period and X-ray flux with the theoretical model would establish whether the torque noise is caused by fluctuations in the mass accretion rate.

The Current Evidence

We have just seen that sequences of accurate period and flux measurements can establish unambiguously many properties of neutron stars and accretion flows. Unfortunately, such sequences are not yet available. Nevertheless, some information can be extracted from the current data by comparing theoretical spin-up curves with the time-average values of P, $\dot{P}$, and L available at present, and by comparing neutron star response models with the pulse phase fluctuations observed in Her X-1. One should, however, keep in mind the ambiguities that arise in working with such a limited set of data.

If we consider a collection of pulsating X-ray sources, the theory of disk accretion predicts that they would all lie on the same curve $-\dot{P} = f(PL^{3/7})$ if they all had (1) the same mass M and (2) the same magnetic moment μ. Although all pulsating X-ray sources are not expected to have identical masses and magnetic moments, observed values of $-\dot{P}$ should be *correlated* with observed values of $PL^{3/7}$ if the variation of the mass and magnetic moment from source to source is not too large. Figure 4 shows a plot of observed values of $-\dot{P}$ against $PL^{3/7}$. Such a plot tends to order the sources according to their fastness, since for fixed M and μ the fastness parameter is a function only of $PL^{3/7}$. Shown are the theoretical spin-up curves for three stellar masses, assuming a magnetic moment of 0.48×10^{30} gauss cm^3 and the tensor interaction (TI) neutron star models of Pandharipande, Pines, and Smith (1976). The curve for $M = 1.3\ M_\odot$ is a rough best fit to the observations. Except for Vela X-1, all the sources lie in the shaded region spanned by the curves corresponding to values of $M/M_\odot$ in the range 0.5 - 1.9.

Even though wind theory is not sufficiently advanced to predict the behavior of $\dot{P}$ as a function of the physical conditions in any single source, the wind hypothesis does, under some conditions, predict a correlation between PLT_s and P_{orb} (Ghosh and Lamb 1979b). Here T_s is the spin-up time scale and P_{orb} is the binary orbital period. Figure 5 shows the currently available data for seven well-studied X-ray sources on a plot of log (PLT_s) against log (P_{orb}). Also shown in the figure is the theoretical relation for one plausible set of binary system parameters. Although the observed values of PLT_s lie within an order of magnitude of the values expected theoretically, there is little evidence for any correlation with P_{orb} (the 22^h X-ray variation sometimes observed in X Per is shown in the figure, even though it probably is not the binary period of the source; if this point is given a low weight, there is no evidence for any increase of PLT_s with P_{orb}).

If one assumes that all nine sources are disk-fed, one can estimate the magnetic dipole moment of each star by adjusting μ so that the theoretical spin-up curve passes through the datum of the star (Ghosh and Lamb 1978, 1979b). The inferred moment depends weakly on the mass and equation of state of the neutron star. Acceptable fits are possible for all nine sources, for a mass of $1.3\ M_\odot$, the TI neutron star models of Pandharipande, Pines, and Smith (1976), and magnetic moments in the range $3 \times 10^{29} - 4 \times 10^{32}$ gauss cm^3. Indeed, one can find a set of solutions with magnetic moments all lying within the relatively narrow range $\sim 5 \times 10^{29} - 5 \times 10^{39}$ gauss cm^3 that is consistent with the data on all the measured sources except Vela X-1. A magnetic moment $\sim 10 - 10^2$ times larger than that inferred for the other sources is required in order to fit the relatively long spin-up time scale of Vela X-1. While such a large magnetic moment is certainly allowed by our current understanding of neutron star magnetic fields, the fact that Vela X-1 alone requires such a large value of μ suggests the alternative possibility that Vela X-1 is wind-fed rather than disk-fed (Lamb 1977), in which case it could have a relatively long spin-up time scale even if its magnetic moment were similar to those of the other sources.

Turning to the problem of the dynamical properties of accreting neutron stars, Boynton and Deeter (1979) have used the Uhuru data on Her X-1 to compute the power spectrum of pulse phase fluctuations in this source. They find that this neutron star responds like a rigid body to torque fluctuations on time scales ranging from 1^d to 100^d. Thus, either the crust-superfluid coupling time in Her X-1 is shorter than 1^d or longer than 100^d, or the superfluid moment of inertia must be less than or comparable to that of the crust.

The good agreement between the predictions of disk accretion theory and the observed average spin-up rates of the currently measured sources together with the apparent absence of any correlation between PLT_s and P_{orb} suggests that at least 8 of these sources are disk-fed and that the theory is qualitatively correct. This good agreement also argues that these sources are indeed neutron stars with canonical masses, radii, moments of inertia, and magnetic moments. However, given our present limited information on magnetic moments, wind conditions, and binary system parameters, these conclusions are necessarily very tentative, a situation which underscores the importance of the HEAO-1 experiment.

THE EXPERIMENT

In the following subsections I outline the nature of the HEAO-1 experiment, describing briefly the utilization of HEAO-1 capabilities, the reasons for choosing to study Her X-1 and Vela X-1, and the planned types of studies.

The Contribution of HEAO-1

The HEAO-1 satellite provided the particular combination of capabilities best suited to carry out this pulse timing mission, for

1) The large detector area and pointing ability provide the high average count rate necessary to minimize the counting statistics noise level in the sequence of pulse arrival times;

2) The precision aspect correction associated with pointed observations allows the study of possible correlations between variations in flux and angular velocity; and

3) The long lifetime of the HEAO-1 mission enables exploration of the power spectrum to sufficiently long periods (at least 100 days) to allow a credible test of power law behavior and an adequate frequency range in which to search for dynamical behavior of the neutron star.

The results of this prototype experiment will provide information which is essential for the design of future instrumentation and observing programs to pursue studies of this type.

Choice of Sources

1. Theoretical Motivation. There are specific theoretical expectations of possible differences between the sources of torque fluctuations in fast rotators and slow rotators. Internal torque fluctuations may be more important in the case of slow rotators (Lamb, Pines, and Shaham 1978). However, if the sources are disk-fed, the torque contribution from the region of magnetic coupling between the disk and the star is especially important in fast rotators (Ghosh and Lamb 1978, 1979b). For these reasons, it is important to select examples from both classes for observation and study.

2. Observational Motivation. Because of the extensive observing time required for even a modest characterization of the angular velocity noise in the strongest sources, we have decided to concentrate our initial studies on only two objects, one short period source, Hercules X-1, and one long period source, Vela X-1.

Preliminary analysis of Uhuru data on Hercules X-1 has already indicated the presence of measurable torque noise in this source (Boynton and Deeter 1979). This fact makes the Hercules source a prime candidate for further study. The HEAO-1 data will allow us to carry out on this source the crucial flux-angular velocity correlation analysis discussed below.

Among the long period sources, Vela X-1 provides the best opportunity for torque noise studies. There are preliminary indications that the noise strength characterizing angular velocity fluctuations in this source is roughly 10^3 times larger than that measured in Her X-1 (Becker et al. 1978; Joss 1978). This means that the HEAO-1 observations of Vela X-1, supplemented by previous HEAO-1 and OSO-8 data, should allow us to recover information from the power spectrum over roughly the same frequency range and with roughly the same signal-to-noise ratio as was possible with the Uhuru data on Her X-1.

Types of Studies

1. Power Spectrum Analysis. In this type of study, one constructs a library of pulse arrival times. A polynomial expression for the arrival times is then fit to the observed sequence, and the residuals are used to calculate the power density in pulse phase fluctuations. If torque noise is detected, one can place significant constraints on the internal structure of the neutron star by fitting theoretical stellar response functions to the measured power spectrum. If there are features in the response power spectrum, one can determine directly neutron star structure parameters such as I_c/I, ω_o, and τ. Because I_c/I is a sensitive function of the equation of state, its value together with an estimate of the stellar mass can be used to constrain the equation of state at high densities. The value of the crust-superfluid coupling time τ can be compared directly with theoretical estimates, while the value of ω_o can be compared with the frequencies of expected internal modes.

2. Studies of X-ray Flux and Angular Velocity Correlations. In this approach, both a sequence of pulse arrival times and a corresponding sequence of X-ray flux determinations are obtained. As emphasized in § II, such a set of paired measurements is a crucial diagnostic tool for establishing the source of any torque fluctuations, since observation of a correlation between the flux and the rate of change of the angular velocity would indicate that the source of the torque fluctuations is external rather than internal. Moreover, the nature of this correlation could then be compared with the detailed predictions of accretion theory to test that theory. If correlations are adequately described by the theory, it would then be possible to distinguish between disk and spherical accretion. In the case of disk accretion, further analysis could lead to an estimate of the neutron star magnetic moment and could even provide constraints on the equation of state of neutron matter. The knowledge of the neutron star response function obtained from the power spectrum analysis is essential to carry out this second phase of analysis, since without knowing the stellar response, it is impossible to determine the torque by working backwards from the crustal angular velocity changes.

3. Searches for Individual Torque Events. In this type of study, one searches the pulse arrival times for relatively rare, very large pulse phase changes. If such events are found, the torque noise process has been at least partially resolved. By resolving the noise process, one can determine the sign distribution of the torque excursions, their characteristic rise and fall times, and their mean rate of occurrence as a function of size. This information can then be compared with the expected properties of accretion and internal torque fluctuations. Again, a knowledge of the neutron star response is essential.

CURRENT STATUS

A total of 11 pointed observations of Vela X-1 were made by HEAO-1 during November and December of 1978. A further pointed observation of Vela X-1 was contributed by SAS-3 in January of 1979, after HEAO-1 pointing capability was lost. These observations were carefully arranged to allow us to construct a pulse phase power density spectrum of the type described in § IIb, with a minimum number of pointings. In addition, arrangements have been made to supplement this data set with several days of OSO-8 observations obtained earlier by the Goddard Space Flight Center X-ray group and HEAO-1 observations obtained by that group during May 1978. The Goddard Space Flight Center group are also contributing several days of OSO-8 observations of Her X-1 and HEAO-1 observations of Her X-1 during February and August 1978.

Some 10 hours of the Her X-1 data from HEAO-1 observations during February 1978 have been furnished to the guest investigators and have been analyzed by Boynton and Deeter. The torque noise power spectrum constructed for Her X-1 with this new data included is shown in Figure 6. The flat spectrum at low frequencies is the white torque noise indicated by the Uhuru data. The three highest frequency points are those obtained from the first HEAO-1 data. They are in the counting-noise-dominated part of the spectrum, but lie somewhat higher than expected for counting noise alone. This indicates that there are indeed pulse shape changes in Her X-1 on time scales of 10 minutes or so. Other evidence for such changes has been reported previously by the Goddard group.

Analysis programs have been developed over several months, and plans have been made to analyze rapidly the remaining observations as they become available.

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TABLE 1

GOALS OF THE HEAO-1 TIMING EXPERIMENT

As a probe of neutron stars:

- Determine mass, radius, inertial, and magnetic moments
- Search for evidence of neutron superfluidity
- Determine ratio of inertial moments of crust and core
- Search for internal resonant modes
- Search for evidence of internal torque fluctuations

As a probe of accretion flows:

- Determine flow pattern (disk-fed or wind-fed)
- Test accretion theory quantitatively
- Investigate fluctuations in flows

TABLE 2

POSSIBLE SOURCES OF TORQUE FLUCTUATIONS

External	Internal
Fluctuations in $\dot{M}$	Crustal fracture
Fluctuations in flow pattern	Vortex unpinning in crust
Flow reversals	Stochastic spin-up of superfluid core

TABLE 3

COMPARISON OF CHOSEN SOURCES

Her X-1	Vela X-1
Detectable white torque noise is present	Evidence for torque noise with a strength $\sim 10^3$ that in Her X-1
Fast rotator	Slow rotator?
Disk-fed	Wind-fed?

TABLE 4

METHOD OF DATA ANALYSIS

Power Spectrum Analysis

Confirm statistical description

Determine torque noise spectrum

Measure or constrain τ and I_s/I_c

— First evidence for superfluid in X-ray stars

— Compare τ with theory

— Help choose correct equation of state

Measure or constrain ω_o

— Compare with theory

$\dot{P}$/Flux Correlation Analysis

Establish character of torque noise (external or internal)

Construct observed $\dot{P}(L)$ curves

— Flow pattern

— Test theory

— Determine magnetic moment

— Constrain M, R, I

Pulse Shape Analysis

New evidence concerning pulse formation

Resolve Noise Process

Rise and fall times

Event size versus frequency

Event sign distribution

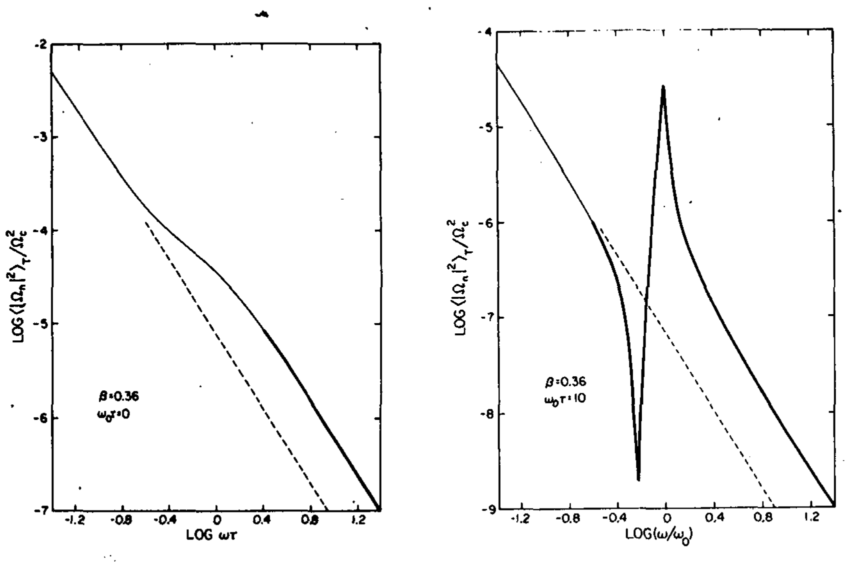

Figure 1. Power density spectra of fluctuations in the crustal angular velocity excited by white torque noise for (a) a neutron star with no internal modes and (b) a neutron star with a single internal mode. From Lamb, Pines, and Shaham (1978).

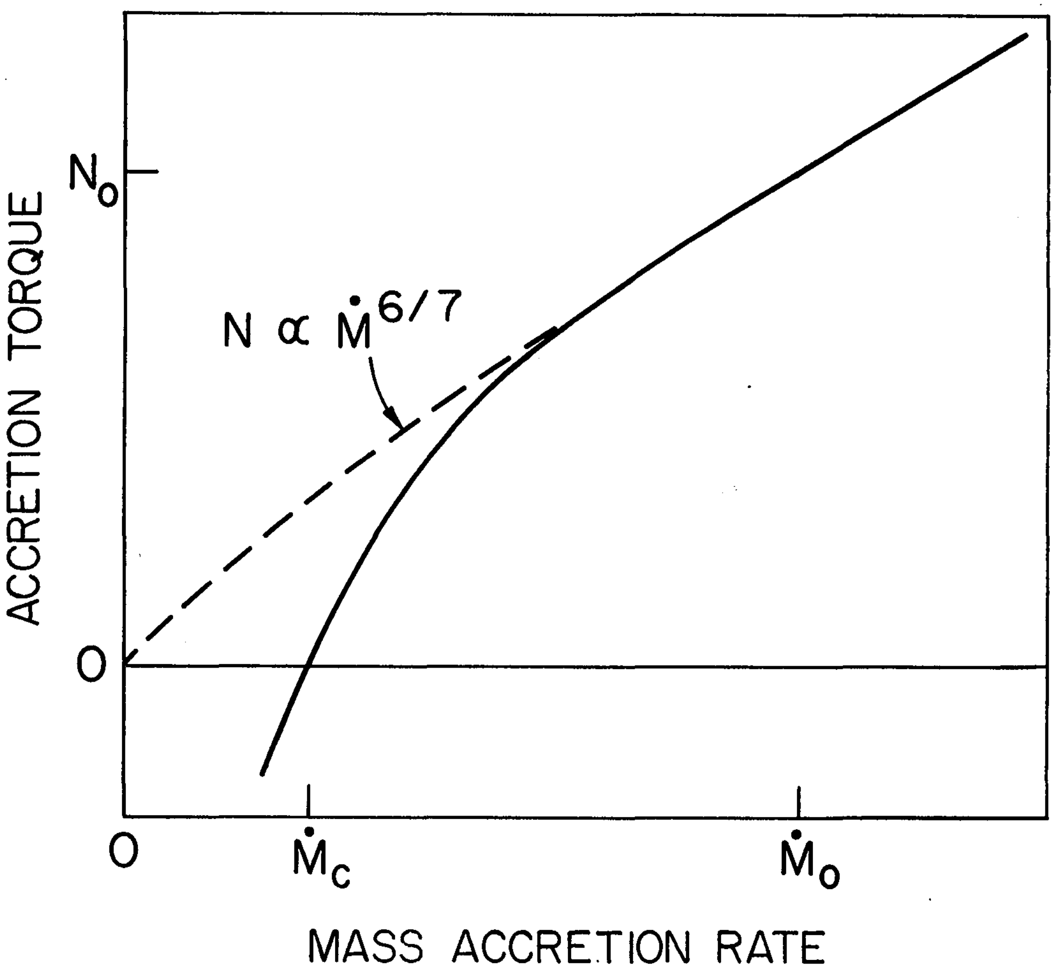

Figure 2. Torque curve predicted by disk accretion theory. From Lamb (1977).

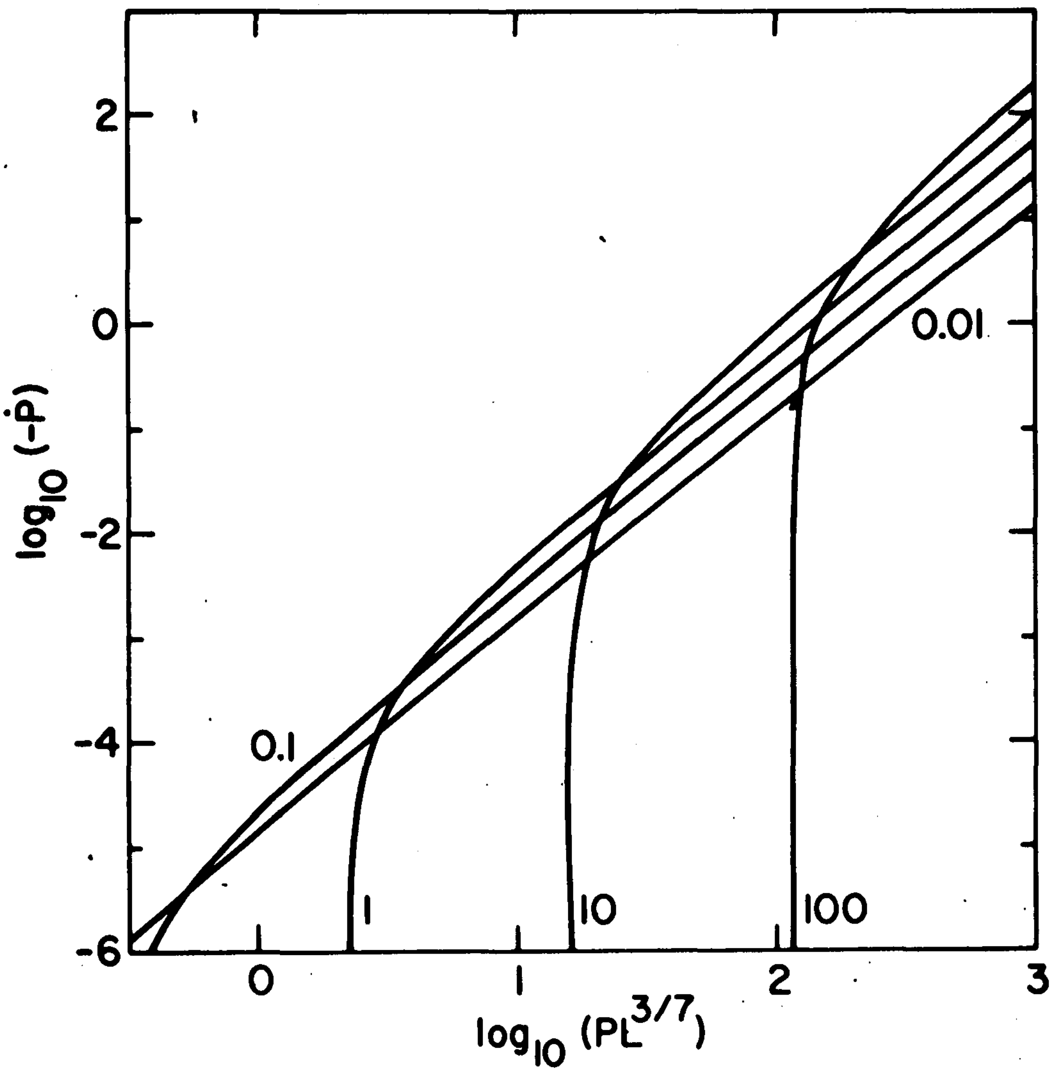

Figure 3. Spin-up curves for a neutron star with a constant effective moment of inertia and various magnetic moments, in units of 10^{30} gauss cm^3. From Ghosh and Lamb (1979b).

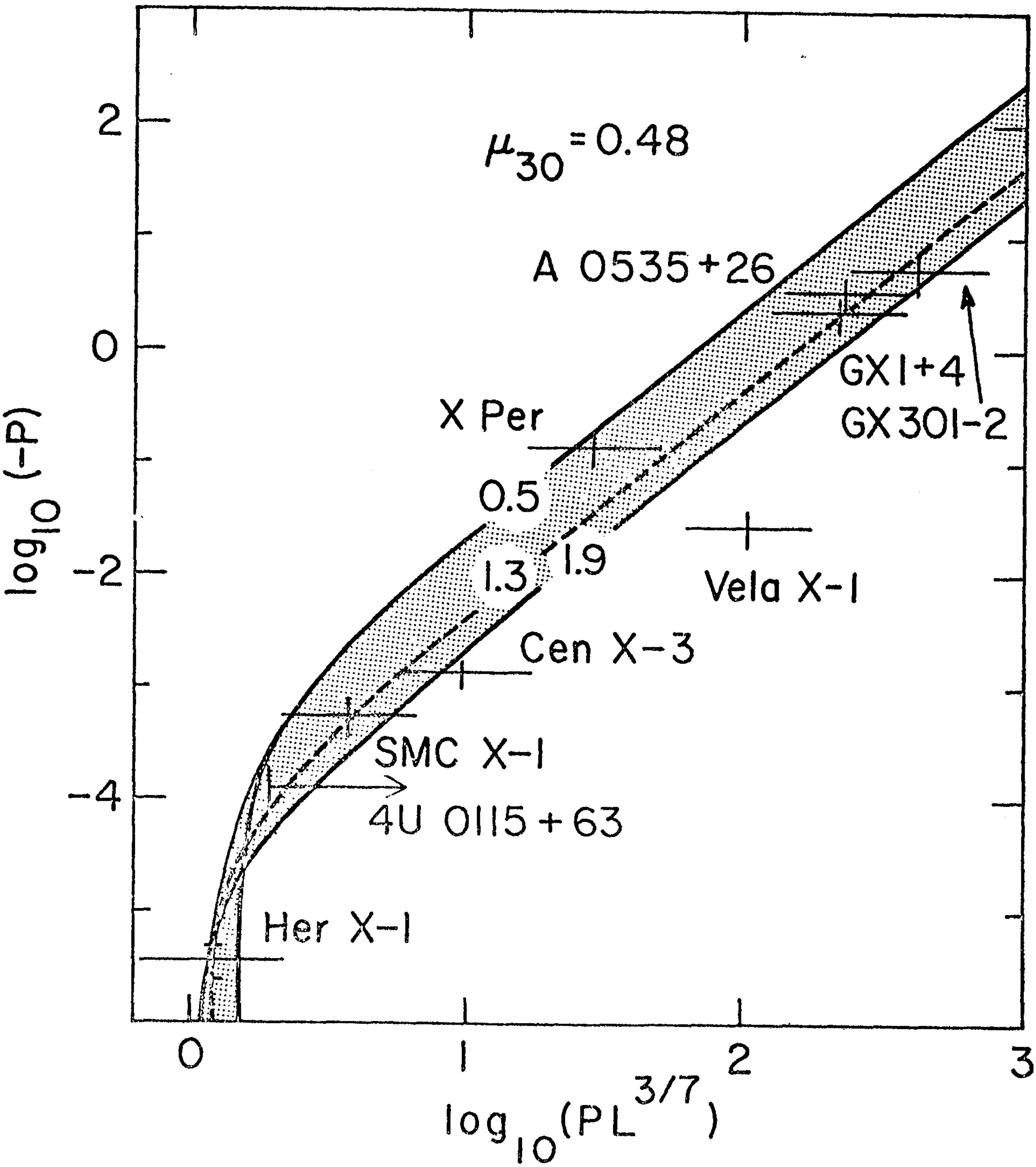

Figure 4. Spin-up curves for three neutron star masses, superimposed on the average values of $-\dot{P}$ and $PL^{3/7}$ for 9 sources. From Ghosh and Lamb (1979b).

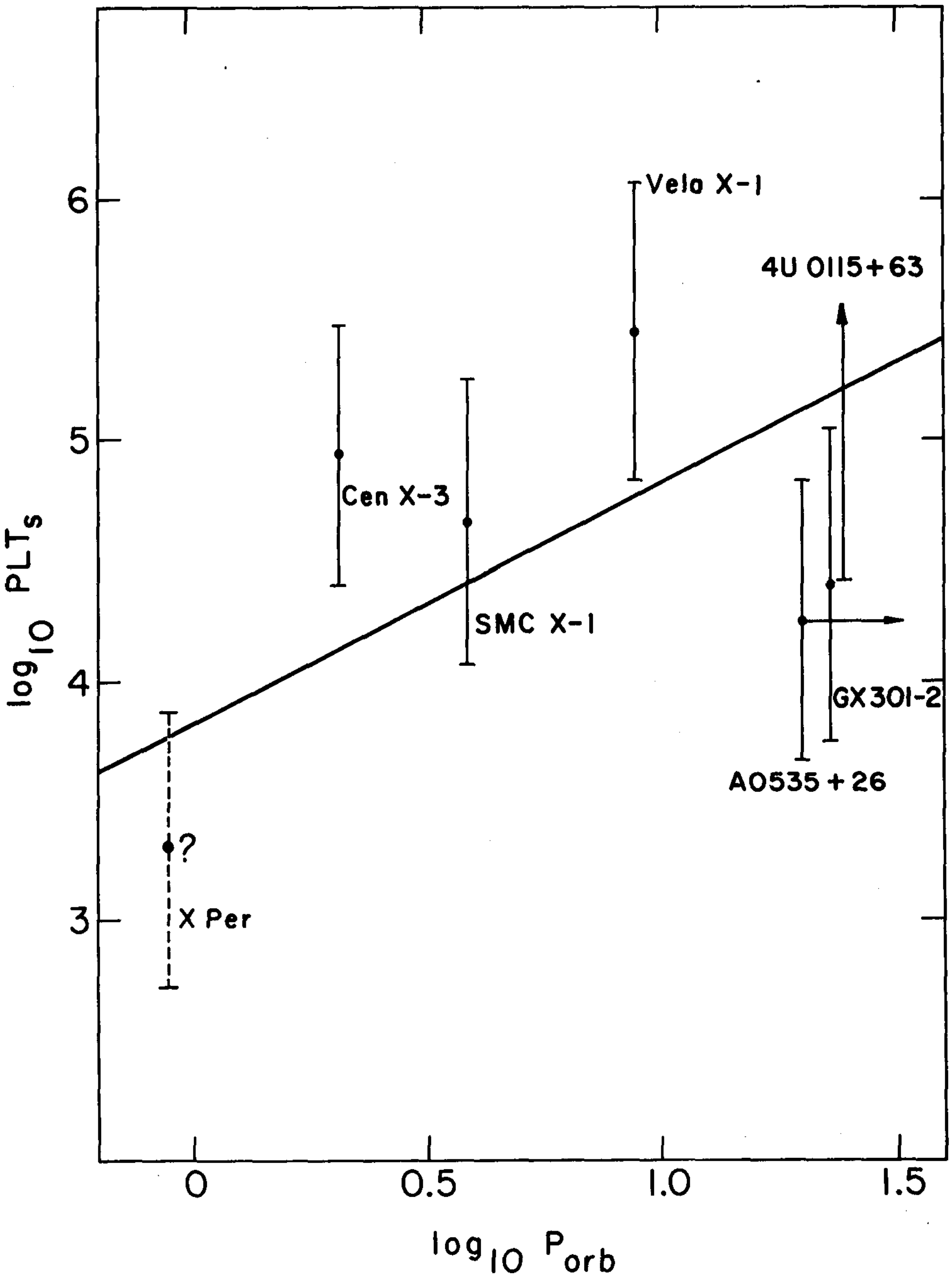

Figure 5. Observed values of PLT_s plotted against observed values of P_{orb} for 7 sources. The straight line is the theoretical relation expected for wind-fed sources under certain conditions. From Ghosh and Lamb (1979b).

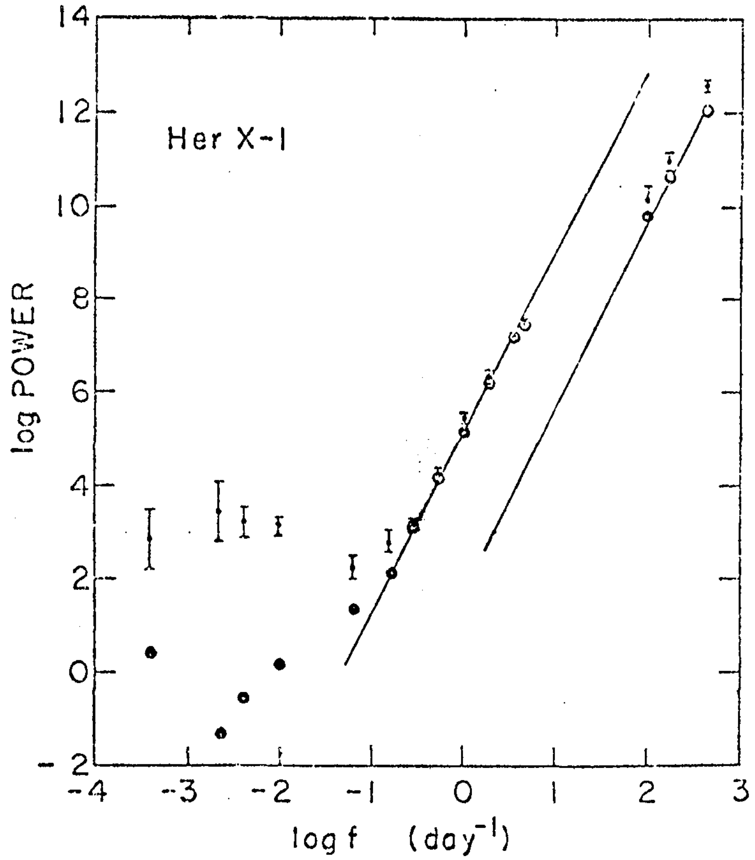

Figure 6. Power density spectrum of fluctuations in crustal angular accelerations in Her X-1, constructed from Uhuru and HEAO-1 A-2 data. From Boynton and Deeter (1979).