THE ASTROPHYSICAL JOURNAL, **266**:769–775, 1983 March 15

X-RAY OBSERVATIONS OF 4U 1626–67 BY THE MONITOR COUNTER ON THE EINSTEIN (*HEAO 2*) OBSERVATORY

R. F. ELSNER, W. DARBRO, D. LEAHY[1], AND M. C. WEISSKOPF
Space Sciences Laboratory, NASA Marshall Space Flight Center
P. G. SUTHERLAND[2]
Department of Physics, McMaster University
AND
S. M. KAHN AND J. E. GRINDLAY[2]
Harvard-Smithsonian Center for Astrophysics
Received 1982 May 10; accepted 1982 September 3

ABSTRACT

We present the results of new X-ray observations of the 7.7 s pulsing X-ray source 4U 1626–67 with the Monitor Proportional Counter on board the *Einstein* (*HEAO 2*) *X-Ray Observatory*. The mean 2–10 keV X-ray luminosity during these observations was $(6.1 \pm 0.3) \times 10^{34}\, d^2$ ergs s^{-1}, where d is the distance in kpc. The 1–21 keV spectrum varies significantly on a time scale of minutes. These data show flares similar to those discovered in *SAS 3* data. The spectral variations do not correlate with the intensity variations. At the reported orbital period of 41.5 minutes, we find an upper limit to the value of the projected semimajor axis of the X-ray source orbit of 0.05 lt-sec, providing confirmation for somewhat lower limit (0.04 lt-sec) set by *HEAO 1* data. The pulse period continues to decrease with time at an average rate $\dot{P} = -(4.9 \pm 0.1) \times 10^{-11}$s s^{-1}, but we find that period variations other than simple spin-up at a constant rate occur in this source and present evidence for an episode of spin-down. The 1–21 keV 7.7 s pulse shape varies significantly on a time scale of minutes. The pulse shape variations correlate in a complex way with the intensity variations but, despite the strong energy dependence of the average X-ray pulse profile, appear not to correlate with the spectral variations.

Subject headings: stars: individual — X-rays: binaries

I. INTRODUCTION

The X-ray source 4U 1626–67 (Forman *et al.* 1978) has received considerable attention in the past few years because of its many interesting and unique properties. Its X-ray emission is pulsed with a period of 7.7 s (Rappaport *et al.* 1977) and is highly variable, with quasi-periodic flares occurring approximately every 1000 s (Joss, Avni, and Rappaport 1978; Li *et al.* 1980) and with changes in its average intensity occurring on a time scale of months (Pravdo *et al.* 1979). The X-ray pulse profile is highly energy dependent (Rappaport *et al.* 1977), and the X-ray spectrum exhibits a corresponding strong pulse phase dependence (Pravdo *et al.* 1979). The weak optical counterpart to 4U 1626–67 (McClintock *et al.* 1977; see also Grindlay 1978, McClintock *et al.* 1980, and Peterson *et al.* 1980) also exhibits 7.7 s optical pulses (Ilovaisky, Motch, and Chevalier 1978). Recent careful timing of these optical pulses by Middleditch *et al.* (1981) together with the lack of observed orbital variations in the X-ray arrival times indicates that the X-ray source is the more massive member of a close 41.5 minute binary system and confirms the low mass binary picture for 4U 1626–67 suggested by Joss, Avni, and Rappaport (1978).

In this paper we present the results of new X-ray observations of 4U 1626–67 with the Monitor Proportional Counter (MPC) on board the *Einstein* (*HEAO 2*) *X-Ray Observatory* (Giacconi *et al.* 1979). We briefly describe the observations and the instrument in § II, and we present the spectral and timing results in § III and § IV, respectively.

II. OBSERVATIONS

The pulsing X-ray source 4U 1626–67 was observed with the MPC on three occasions in early 1979 (see Table 1). The MPC is a sealed, argon-filled proportional counter with a 1.5 mil beryllium window and is co-aligned with the X-ray telescope on board the observatory. The spectral data spanning the energy range 1.1–21 keV are divided into eight logarithmically spaced energy channels which integrate for 2.56 s. The Time Interval

[1]NAS/NRC Resident Research Associate.
[2]Alfred P. Sloan Foundation Fellow.

TABLE 1

MPC/TIP X-RAY OBSERVATIONS OF 4U 1626−67

Date	Time Span (s)	Integration Time (s)	Rate (counts s^{-1})[a]
1979 Feb 24 ...	5500	2300	34.4
1979 Mar 10 ...	14,500	3000	31.6
1979 Mar 14 ...	18,000	6600	29.8

[a] Background subtracted.

Processor (TIP) circuitry of the MPC measures time intervals between events to within 1 μs or 1.6%, whichever is larger, for a count rate dependent fraction of all events in all eight energy channels. The TIP data are separate from the MPC spectral data and provide high time resolution but no spectral information. Gaillardetz *et al.* (1978) and Grindlay *et al.* (1980) give detailed discussions of the MPC and TIP.

III. SPECTRAL RESULTS

We analyzed the spectral data from the MPC using the methods outlined in Grindlay *et al.* (1980). The average 2–10 keV X-ray luminosity during these observations was $(6.1 \pm 0.3) \times 10^{34}$ d^2 ergs s^{-1}, and the average 2–10 keV energy power law index was -0.65 ± 0.05. Here d is the distance to 4U 1626−67 in kpc. The 2–10 keV spectrum agrees with that obtained during the earlier *HEAO 1* observations (Pravdo *et al.* 1979) except that the intensity is only 80% of that observed by *HEAO 1*. The 1.1–21 keV luminosity during these MPC observations was 1.8–2.0×10^{35} d^2 ergs s^{-1}, assuming a spectrum similar to that described by Pravdo *et al.*

Figure 1 displays the background subtracted 1.1–21 keV TIP count rate as a function of time for all of the data taken on UT 1979 March 14. The methods of background determination and of rejection of high background data are described by Grindlay *et al.* (1980). The background is typically about 17.5 counts s^{-1} and is conservatively estimated to be accurate within 0.5 counts s^{-1} (Halpern and Grindlay 1983). The large gaps are due to Earth occultations, passage through the South Atlantic Anomaly, etc. Large intensity fluctuations are apparent from this figure; these undoubtedly reflect the same phenomena underlying the 1000 s quasi-periodic oscillations discovered during *SAS 3* observations of 4U 1626−67 (Joss, Avni, and Rappaport 1978; Li *et al.* 1980).

It is interesting to note that the MPC data provide no convincing evidence for spectral changes correlated with the flares, although spectral variability is apparent in the data. In order to quantitatively test for correlations between spectral changes and intensity variations, hardness ratios, defined as the ratio of the background subtracted counts over the ranges 6.44–20 keV to the background subtracted counts over the range 1.1–6.44 keV, were computed for each 4.096 minute interval of data. *Although the hardness ratios, plotted in Figure* 2 *versus background subtracted TIP count rate, exhibit significant variability, we find no evidence for correlation between hardness ratio and intensity.*

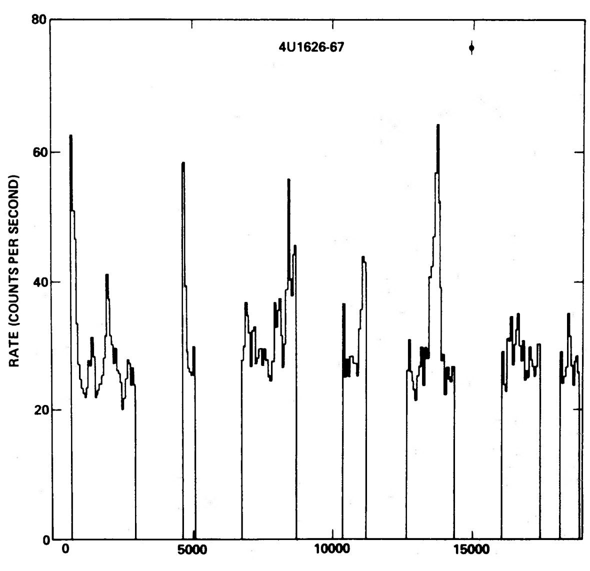

FIG. 1.—The background subtracted TIP counting rate binned on a 1 minute time scale for the pulsing X-ray source 4U 1626−67 on UT 1979 March 14. The vertical bar in the upper right shows the typical ± 1 σ error due to counting statistics.

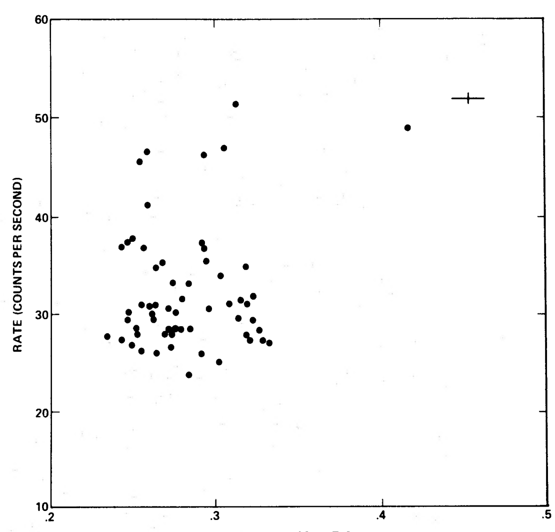

FIG. 2.—Scatter plot of hardness ratio as defined in the text vs. background subtracted count rate. The data points were generated from 4.096 minute integrations. There is no apparent correlation between hardness ratio and count rate.

IV. TIMING RESULTS

For each day's observations, the TIP data were converted to photon arrival times at the solar system barycenter, and pulse arrival time analysis was used to determine the best value of the pulse period, and to search for possible orbital motions of the X-ray source. We selected an initial trial period and constructed a binned representation for the template of the pulse profile by epoch-folding the day's data at periods near the value expected on the basis of earlier X-ray observations and requiring that the χ^2 of a fit to an unpulsed source be at its maximum. Deeter (1981) has recently emphasized the importance of removing from the template harmonics which do not stand out above the noise, so we generated a continuous (in pulse phase) representation for the template by Fourier analyzing the binned representation and keeping only those harmonics (the first six in this case) with amplitudes significantly larger than the noise level expected from counting statistics. Pulse arrival times were determined for 4 minute sections of data by cross correlating the sample pulse profiles with the template. Since the phase shifts were small, Taylor's expansion of the cross correlation function permitted direct solution for the phase shift. Errors were set by propagation of errors due to counting statistics.

For each day's data, the set of arrival times was consistent with a constant period and showed no evidence for orbital motion at the 41.5 minute binary period reported by Middleditch *et al.* (1981). For a circular orbit, the upper limit to the value of the projected semimajor axis ($a_x \sin i$) for the X-ray source is 0.05 lt-sec at the 95% (2 σ) confidence level. This confirms the slightly lower value of 0.04 lt-sec that Middleditch *et al.* (1981) set from analysis of *HEAO 1* data. As fully described by those authors, this upper limit together with their timing analysis of the optical pulses provides strong support for the low-mass binary picture of the 4U 1626−67 system proposed by Joss, Avni, and Rapport (1978).

Table 2 and Figure 3 display the results of our three measurements of the pulse period together with all earlier X-ray measurements, while Figure 4 shows the 1.1–21 keV pulse profile obtained from folding all the TIP data taken on UT 1979 March 14 at the period given in Table 2. Our three points alone are clearly not consistent within their errors with steady spin-up at a constant rate. In fact, the pulse period measured for UT 1979 March 10 is shorter than that for UT 1979 March 14, just four days later, providing evidence for an actual spindown episode ($\Delta P = 0.000067 \pm 0.000027$ s).

TABLE 2

X-RAY MEASUREMENTS OF THE 4U 1626−67 PULSE PERIOD

Date (UT)	P (s)	References
1977 Mar 24.4 ...	7.6806273 ± 0.0000005	1
1978 Mar 29.6 ...	7.679190 ± 0.000025[a]	2
1978 May 29.9 ...	7.67893 ± 0.00002	3
1979 Feb 24.6	7.677765 ± 0.000064	4
1979 Mar 10.1 ...	7.677565 ± 0.000024	4
1979 Mar 14.0 ...	7.677632 ± 0.000013	4

[a] The 1σ error listed here is half the 2 σ error given in the reference cited.

REFERENCES.—(1) Joss, Avni, and Rappaport 1978. (2) Pravdo *et al.* 1979. (3) McClintock *et al.* 1980. (4) This work.

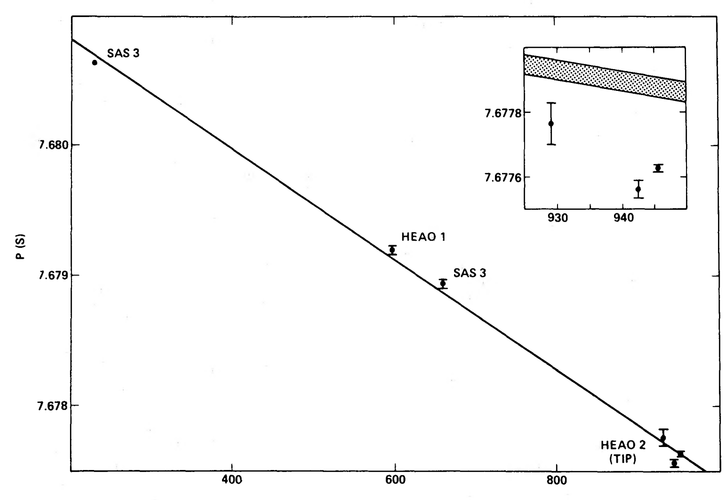

FIG. 3.—The X-ray period history for 4U 1626−67. The straight line represents the function $P(t) = P_0 + \dot{P}t$ with $\dot{P} = -(4.9 \pm 0.1) \times 10^{-11}$ s s^{-1}, as determined from an unweighted fit to the data in Table 2. The error on the first *SAS 3* point is too small to show on the figure. The insert gives an expanded scale view of the region containing the TIP data points. Here the shaded area is that expected on the basis of extrapolation of the *SAS 3* results of Joss, Avni, and Rappaport 1978.

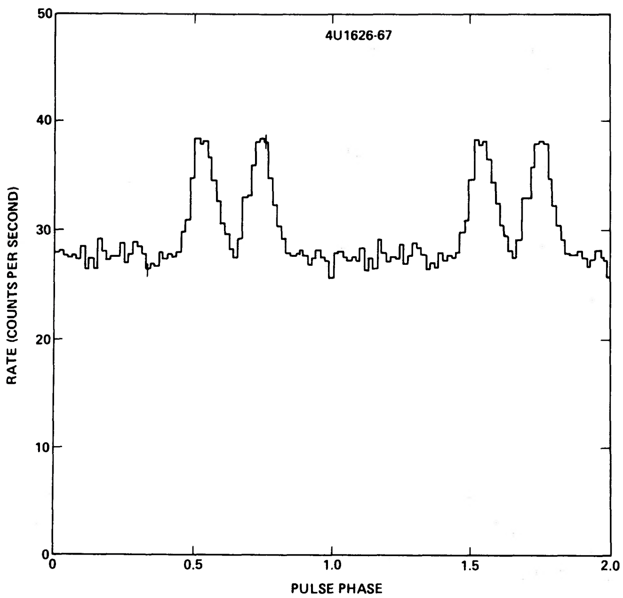

FIG. 4.—The 4U 1626−67 X-ray pulse profile with background subtracted obtained by folding the TIP data taken on UT 1979 March 14 at the period given in Table 2. Also shown are the largest and smallest $\pm 1\ \sigma$ error bars based on counting statistics.

The complete set of X-ray measurements of the pulse period clearly shows a trend toward spin-up as expected for a rotating neutron star acted upon by accretion torques (Ghosh and Lamb 1979 and references therein), but provides further evidence for period behavior more complicated than simple spin-up at a constant rate. First, as shown in the inset to Figure 3, the period measurements reported here fall significantly below the range of values expected for the epoch of observation based on an extrapolation of *SAS 3* results (Joss, Avni, and Rappaport 1978). Second, the data in Table 2 provide an extremely poor fit to the functional form appropriate for spin-up at a constant rate. The best value for the period derivative based on an unweighted fit to the data in Table 2 is $\dot{P} = -(4.9 \pm 0.1) \times 10^{-11}$ s s^{-1}, where the error is determined from the scatter of the data about the best fit line. The corresponding value for the spin-up time scale is $|P/\dot{P}| = (5.0 \pm 0.1) \times 10^3$ yr, in approximate agreement with previous results (Joss, Avni, and Rappaport 1978; Pravdo *et al.* 1979).

Figure 5 shows six examples of 4 minute sample pulse profiles; examination of these and the other samples suggested to us that the X-ray pulse profile varies with time. In order to explore this possibility further we Fourier analyzed each of the sample pulses and constructed a smoothed sample pulse given by

$$\lambda(t) = \lambda_0 \left[1 + \sum_{k=1}^{6} a_k \cos(2\pi k t / P + \phi_k) \right]. \quad (1)$$

Here λ_0 is the average background subtracted count rate for the 4 minute sample, a_k the dimensionless relative amplitude of the kth harmonic, and ϕ_k the phase of the kth harmonic. If the pulsed fraction, f, is defined as the ratio of the pulsed flux (i.e., the component above the constant level) to the total flux, then f is given by

$$f = 1 - \lambda_{\min}/\lambda_0 = -\sum_{k=1}^{6} a_k \cos(2\pi k t_{\min}/P + \phi_k), \quad (2)$$

where the minimum value for $\lambda(t)$ is $\lambda_{\min} = \lambda(t_{\min})$. The values for f generated in this way from the MPC/TIP data for 4U 1626−67 are quite consistent with a *constant* pulsed fraction and lead to a best fit value $f_0 = 0.17 \pm 0.01$. On the other hand, the values for a_1 are not consistent with constant behavior, the variance exceeding that expected on the basis of counting statistics by the factor of 2.5. These seemingly contradictory results are reconciled if the shape of the pulse profile varies with time.

In order to verify this result and to connect it with other properties of the source, we applied a linear corre-

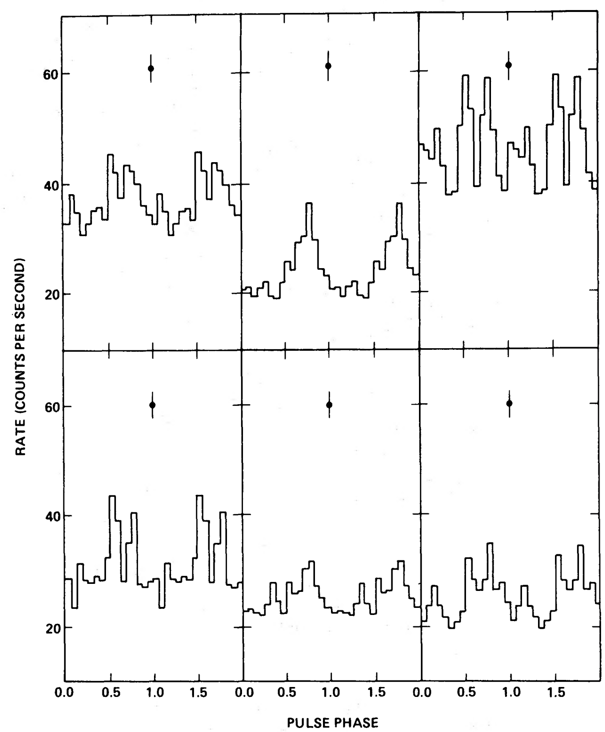

FIG. 5.—Six sample X-ray pulse profiles, each obtained by folding a 4.096 minute section of data, showing variability of the pulse shape. The bottom left example most resembles the average profile shown in Fig. 4 and is perhaps most representative. Typical $\pm 1\ \sigma$ error bars based on counting statistics are shown in the upper center of each plot.

lation analysis. For two variables X and Y, an estimate of linear correlation coefficient, r, is given by (see, e.g., Smillie 1966)

$$r=\sum_{i=1}^{n}(X_i+\bar{X})(Y_i-\bar{Y})/(n-1)(s_X s_Y)^{1/2}, \quad (3)$$

where n is the number of samples, $\bar{X}$ and $\bar{Y}$ are the sample means for X and Y, and s_X and s_Y are the sample variances. As is well known, the expectation value for r is $+1$ if X and Y are perfectly correlated and -1 if they are perfectly anticorrelated. The expectation value for r is zero if X and Y are completely independent. A convenient procedure for testing the statistical significance of a measured value for r is provided by Fisher's transformation (see, e.g., Smillie 1966)

$$z=0.5\ln[(1+r)/(1-r)]. \quad (4)$$

For normally distributed data, the transformed correlation coefficient z is also normally distributed with mean $0.5\ln[(1+R)/(1-R)]$, where R is the true value of the linear correlation coefficient. The statistical significance for a value of z derived from equation (4) is estimated by comparing it to the standard deviation of the transformed correlation coefficient, $\sigma_z=(n-3)^{-1/2}$.

We used the procedure just described to look for correlations of a_k with λ_0, f, H, and $\Delta\phi_k$; and of $\Delta\phi_k$ with λ_0, f, and H. Here H is the hardness ratio, defined in § III, for the 4 minute sample; $\Delta\phi_k$ is the phase difference from the template for the kth harmonic of the sample pulse; and the index k runs from 1 to 6. We repeated the analysis substituting the absolute amplitude, $A_k=\lambda_0 a_k$, for the relative amplitude, a_k. Significant correlations were found only for harmonic amplitudes versus count rate and, less significantly, pulsed fraction (Tables 3 and 4); in particular, no correlations were found for hardness ratios versus any pulse profile parameter (Table 5). The most significant results are the relatively strong anticorrelation of a_1 with λ_0 and the relatively strong correlation of A_3 with λ_0 (Fig. 6). Marginal results are the apparent correlations of a_1, a_6, and A_1 with f; the apparent anticorrelation of a_2 and a_5 with λ_0; and the apparent correlation of A_4 and A_6 with λ_0. If the pulse shape were constant and independent of source count rate and if the pulse fraction were changing, then all a_k would be correlated with f but uncorrelated with λ_0, while all A_k would correlate with λ_0. Therefore, these results provide strong evidence for pulse shape variability.

The different correlations between individual harmonic amplitudes and count rate described above imply a complicated relation between precise pulse shape and observed source intensity. We note that as mass accretion rate increases the magnetosphere of the neutron star shrinks slightly (see, e.g., Lamb, Pethick, and Pines 1973). This in turn leads to a small increase in the extent of the X-ray emitting hot spots at the magnetic poles

TABLE 3

LINEAR CORRELATIONS OF HARMONIC AMPLITUDES WITH COUNT RATE[a]

		HARMONIC NUMBER					
CASE	COEFFICIENT[b]	1	2	3	4	5	6
Relative amplitudes (a_k)	r	−0.49	−0.30	+0.14	−0.20	−0.33	−0.12
	z	−0.53	−0.31	+0.14	−0.20	−0.34	−0.12
Absolute amplitudes (A_k) ...	r	+0.03	+0.08	+0.48	+0.34	+0.12	+0.30
	z	+0.03	+0.08	+0.53	+0.35	+0.12	+0.31

[a]Background subtracted.
[b]The correlation coefficients r and z are defined and discussed in the text. For all entries, $\sigma_z=0.13$.

TABLE 4

LINEAR CORRELATIONS OF HARMONIC AMPLITUDES WITH PULSED FRACTION[a]

		HARMONIC NUMBER					
CASE	COEFFICIENT[b]	1	2	3	4	5	6
Relative amplitudes (a_k)	r	0.40	0.11	−0.01	0.18	0.14	0.31
	z	0.43	0.12	−0.01	0.18	0.14	0.32
Absolute amplitudes (A_k) ...	r	0.34	0.10	−0.07	0.09	0.07	0.26
	z	0.35	0.10	−0.07	0.09	0.07	0.27

[a]Defined by eq. (2).
[b]The correlation coefficients r and z are defined and discussed in the text. For all entries, $\sigma_z=0.13$.

1983ApJ...266..769E

TABLE 5

Linear Correlations of Harmonic Amplitudes with Hardness Ratio[a]

Case	Coefficient[b]	Harmonic Number 1	2	3	4	5	6
Relative amplitudes (a_k)	r	+0.03	−0.04	−0.12	−0.26	−0.10	−0.04
	z	+0.03	−0.04	−0.12	−0.26	−0.10	−0.04
Absolute amplitudes (A_k) ...	r	+0.09	−0.05	−0.07	−0.24	+0.01	−0.04
	z	+0.09	−0.05	−0.07	−0.25	+0.01	−0.04

[a]Defined as the ratio of the background subtracted counts from 6.44–20 keV to the background subtracted counts from 1.1–6.44 keV for each 4.096 minute interval of data.

[b]The correlation coefficients r and z are defined and discussed in the text. For all entries, $\sigma_z = 0.13$.

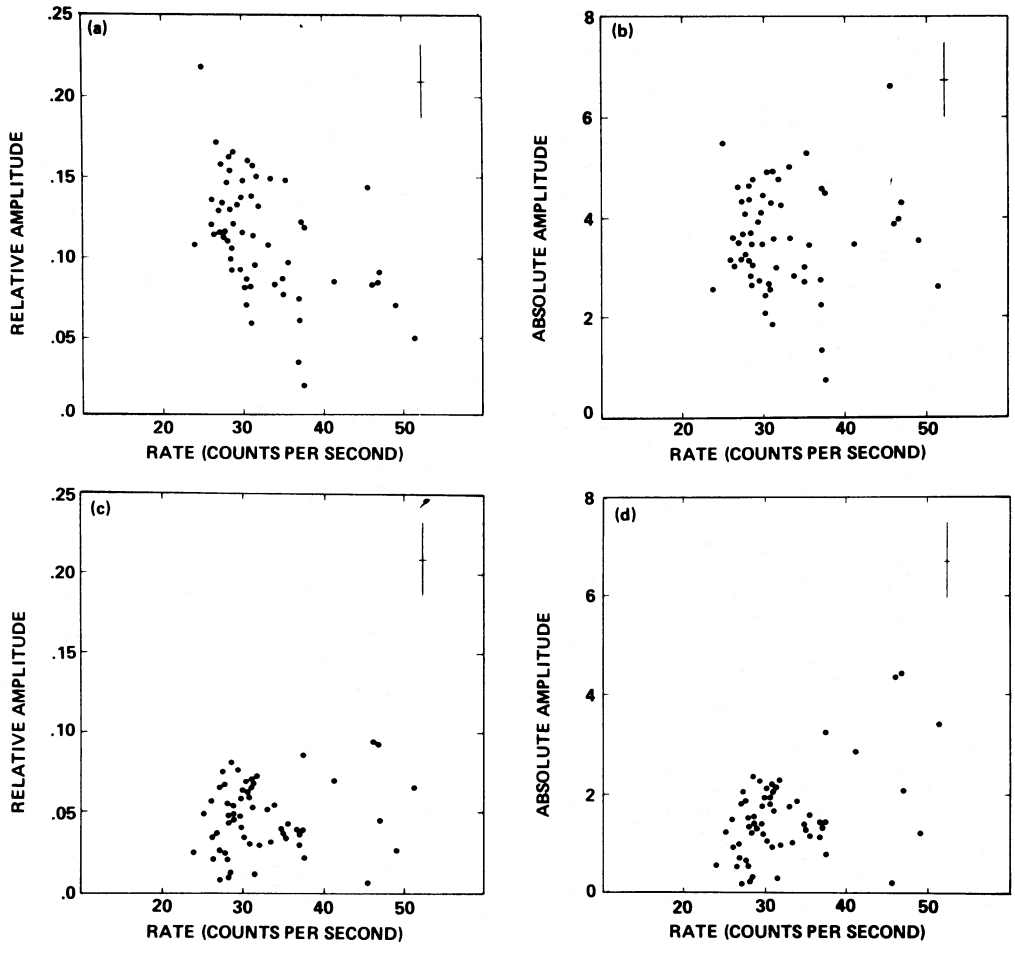

Fig. 6.—Scatter plots of harmonic amplitude vs. 4.096 minute sample averaged count rate (background subtracted) with typical error bars based on counting statistics shown in the upper right of each plot: (a) relative amplitude (see text) of first harmonic vs. rate for which we find significant anticorrelation (see Table 3); (b) absolute amplitude (in counts s^{-1}) of first harmonic vs. rate for which we find no correlation; (c) relative amplitude of third harmonic vs. rate for which we find no correlation; and (d) absolute amplitude of third harmonic vs. rate for which we find significant correlation.

(Elsner 1976) and in the amount of matter able to penetrate deep into the magnetosphere away from the magnetic poles (Elsner and Lamb 1976, 1977). If the surface field of the neutron star is at all complex, then even small changes in the configuration of the magnetosphere can lead to complicated changes in the X-ray pulse profile (Elsner and Lamb 1976). If the intensity variations observed in 4U 1626−67 are due to variations in mass accretion rate, then it is perhaps not surprising that complicated correlations exist between the pulse shape and count rate.

V. CONCLUDING REMARKS

We have found that in the energy range 1–21 keV, the spectrum and 7.7 s pulse shape of 4U 1626−67 are variable on a time scale of minutes. The pulse shape variations correlate in a complex way with the intensity variations in this source. It is perhaps surprising that the hardness ratio variations appear to show no correlation with the intensity variations or, especially in view of the strong energy dependence of the X-ray pulse profile (Rappaport *et al.* 1977; Pravdo *et al.* 1979), with the pulse shape variations. On the other hand, present understanding of the intensity variations in 4U 1626−67 is limited, and theoretical models for the pulse formation process in pulsing X-ray sources are primitive. One may expect that the spectral and pulse shape variability established by the MPC/TIP data for 4U 1626−67, will provide future, more sensitive studies with valuable tools for increasing understanding of this and other pulsing X-ray sources. In particular, further observational and theoretical work on the correlations (or lack thereof) between these phenomena and the intensity variations may clarify the latter's origin. Possibilities include episodic obscuration of the X-ray source and modulation of the accretion flow either at the companion, or within an accretion disk, or at the magnetospheric boundary, or within the magnetosphere (see Li *et al.* 1980).

Finally, in addition to measuring the average rate of spin-up of 4U 1626−67 over a period of 2 years, we have shown that period variations other than simple spin-up at a constant rate occur in this source and have presented evidence for a spin-down episode. In view of these results and of the intensity variations exhibited by this source, we conclude that 4U 1626−67 is a good candidate for future studies of accretion torques and the neutron star response (for discussions of such studies see Lamb, Pines, and Shaham 1978*a*, *b*; Lamb 1979; Ghosh and Lamb 1979; Boynton and Deeter 1979; and Deeter 1981).

We would like to thank Dr. S. Holt for allowing us to use MPC/TIP data taken with the solid state spectrometer in the focal plane of the X-ray telescope. We are grateful to Prof. F. K. Lamb, Prof. P. Boynton, and Dr. J. Deeter for helpful conservations regarding pulse timing and pulse shape variations.

REFERENCES

Boynton, P., Deeter, J. 1979, in *Compact Galactic X-Ray Sources: Current Status and Future Prospects*, ed. F. K. Lamb and D. Pines (Urbana, Ill.: Physics Department, University of Illinois), p. 168.
Deeter, J. E. 1981, Ph.D. thesis, University of Washington.
Elsner, R. F. 1976, Ph.D. thesis, University of Illinois.
Elsner, R. F., and Lamb, F. K. 1976, *Nature*, **262**, 356.
______. 1977, *Ap. J.*, **215**, 897.
Forman, W., Jones, C., Cominsky, L., Julian, P., Murray, S., Peters, G., Tananbaum, H., and Giacconi, R. 1978, *Ap. J. Suppl.*, **38**, 357.
Gaillardetz, R., Bjorkholm, P., Mastronardi, R., Vanderhill, M., and Howland, D. 1978, *IEEE Trans.*, **NS-25**, 437.
Ghosh, P., and Lamb, F. K. 1979, *Ap. J.*, **234**, 296.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Grindlay, J. E. 1978, *Ap. J.*, **225**, 1001.
Grindlay, J. E., *et al.* 1980, *Ap. J.* (*Letters*), **240**, L121.
Halpern, J. P., and Grindlay, J. E. 1983, in preparation.
Ilovaisky, S. A., Motch, C., and Chevalier, C., 1978, *Astr. Ap.*, **70**, L19.
Joss, P. C., Avni, Y., and Rappaport, S. 1978, *Ap. J.*, **221**, 645.
Lamb, F. K. 1979, in *Compact Galactic X-ray Sources: Current Status and Future Prospects*, ed. F. K. Lamb and D. Pines (Urbana, Ill.: Physics Department, University of Illinois), p. 143.
Lamb, F. K., Pethick, C. J., and Pines, D. 1973, *Ap. J.*, **184**, 271.
Lamb, F. K., Pines, D., and Shaham, J. 1978*a*, *Ap. J.*, **224**, 969.
______. 1978*b*, *Ap. J.*, **225**, 582.
Li, F. K., Joss, P. C., McClintock, J. E., Rappaport, S., and Wright, E. L. 1980, *Ap. J.*, **240**, 628.
McClintock, J. E., Canizares, C. R., Bradt, H. V., Doxsey, R. E., Jernigan, J. G., and Hiltner, W. A. 1977, *Nature*, **270**, 320.
McClintock, J. E., Canizares, C. R., Li, F. K., and Grindlay, J. E. 1980, *Ap. J.* (*Letters*), **235**, L81.
Middleditch, J., Mason, K. O., Nelson, J. E., and White, N. E. 1981, *Ap. J.*, **244**, 1001.
Peterson, B. A., Wallace, P., Elliott, K. H., Hill, P. W., and Manchester, R. N. 1980, *M.N.R.A.S.*, **190**, 33P.
Pravdo, S. H., *et al.* 1979, *Ap. J.*, **231**, 912.
Rappaport, S., Markert, T., Li, F. K., Clark, G. W., Jernigan, J. G., and McClintock, J. E. 1977, *Ap. J.* (*Letters*), **217**, L29.
Smillie, K. W. 1966, *An Introduction to Regression and Correlation* (New York: Academic Press), chap. 2.

W. DARBRO, R. F. ELSNER, D. LEAHY, and M. C. WEISSKOPF: ES62, Marshall Space Flight Center, AL 35812

S. M. KAHN and J. E. GRINDLAY: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

P. G. SUTHERLAND: Department of Physics, McMaster University, Hamilton, Ontario L85 4M1, Canada