THE ASTROPHYSICAL JOURNAL, 231:912–918, 1979 August 1

HEAO 1 OBSERVATIONS OF THE X-RAY PULSAR 4U 1626−67

S. H. PRAVDO,* N. E. WHITE,* E. A. BOLDT, S. S. HOLT, P. J. SERLEMITSOS, J. H. SWANK, AND A. E. SZYMKOWIAK*
Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center
AND
I. TUOHY AND G. GARMIRE
California Institute of Technology
Received 1979 January 3; accepted 1979 February 15

ABSTRACT

We report results of an observation of the 7 s pulsar 4U 1626−67 with the A-2 experiment on *HEAO 1*. The phase-averaged X-ray spectrum between 0.7 and 60 keV is complex, as are the constituent spectra, which change radically as a function of pulse phase. Included in this spectral change is the sudden appearance ($\Delta\phi \leq 0.1$) and subsequent decay of a continuum or emission feature with a mean energy of 19 keV which contains about one-half the power in this spectral range. Pulse timing results include a new determination of the pulse period and a factor 8 reduction in the upper limit for the light travel time for orbital periods between 1 and 7 hours. We discuss these findings for this system and compare them with the general nature of pulsar spectra.

Subject headings: pulsars — X-rays: sources — X-rays: spectra

I. INTRODUCTION

It has been established that X-ray pulsars belong to a spectral class which is characterized by an extremely hard spectrum (power-law index $\alpha \lesssim 1$) in the 2–15 keV energy band (e.g., Ulmer 1975). The 7 s pulse period of 4U 1626−67 was discovered when a crude study of its spectrum (Markert *et al.* 1979) indicated that it was a member of this spectral class and a good candidate for a period search (Rappaport *et al.* 1977). If this pulsar is a member of a binary system, then variations in the pulse arrival times due to radial orbital motion can determine the orbital light travel time ($a_x \sin i$), the orbital period (P_{orb}), and hence the mass function for the system. Rappaport *et al.* did not detect this effect but were able to exclude a significant amount of the $a_x \sin i$ versus P_{orb} plane in parameter space. This result and that of McClintock *et al.* (1977), which suggested a faint blue star as the optical counterpart, led to a model of a binary system containing a neutron star and a low-mass dwarf companion with $P_{orb} \lesssim 7$ hours (Joss, Avni, and Rappaport 1978). The optical identification was confirmed by Ilovaisky, Motch, and Chevalier (1978) when they detected 7 s pulsations from the star.

The pulse profile is very energy-dependent, showing drastic changes in amplitude, phase, and structure over a relatively small energy range (Rappaport *et al.* 1977). However, there have been to date no detailed spectral studies of this source. We present here a *HEAO 1* pointed observation of 4U 1626−67 from which we have been able to obtain pulse phase spectroscopy and further improve the upper limits to orbital motion.

II. THE OBSERVATIONS

The *HEAO 1* A-2 X-ray spectroscopy experiment[1] (Rothschild *et al.* 1978) observed 4U 1626−67 for 5 hours starting at 15 hours UT on 1978 March 29. Three coaligned proportional counters were utilized, each containing a different filling gas. They were (1) propane filled (LED, 0.7–1.9 keV at this time), (2) argon filled (MED, 1.7–18 keV), and (3) xenon filled (HED, 3–60 keV). The MED and HED counts were pulse height analyzed into 64 channels with a temporal resolution of 20 ms. The broad-band accumulation interval of the LED was 80 ms with 10 channel pulse height analysis every 40 s. The diffuse and particle backgrounds were obtained from off-source observations prior to this measurement. The LED background was determined by using a field-of-view subtraction technique.

III. THE PULSE PERIOD

Periodogram analysis of the data revealed the 7.6 s pulse to be clearly present in each of the detectors. The energy-dependent nature of the pulse profile was also evident. In order to maximize the amount of pulse phase information available, the counts were binned into three energy ranges: 0.7–1.9 keV; 3–14 keV; and 14–30 keV. Every 30 minutes of data were folded about the period determined by the periodogram analysis. The phase of each of these light curves relative to an

* Also Department of Physics and Astronomy, University of Maryland.

[1] The A-2 experiment on *HEAO 1* is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at GSFC, CIT, JPL, and UCB.

arbitrary reference point was then determined by fitting each light curve to a standard template. This process was repeated twice, the first time with one of the 30 minute folds used as the template, the second time using a master template constructed by superposing each of the 30 minute light curves (excluding the light curve being fitted) shifted according to the phases determined from the first iteration. The light curves constructed from the second iteration are shown in Figure 1. Six measurements of the pulse phase were obtained in each energy interval with 1 σ uncertainties of 0.07 lt-sec in both the 3–14 and 14–30 keV bands and 0.15 lt-sec in the 0.7–1.9 keV band.

Joss *et al.*, using *SAS 3*, set stringent upper limits to orbital motion with a period greater than 7 hours. However, for periods less than this their upper limit to the projected semimajor axis ($a_x \sin i$) was of the order of only 0.8 lt-sec (Fig. 2). The gross effective area of the A-2 detectors is ~20 times greater than *SAS*. By combining the phase measurements from each energy band we see no evidence for orbital periods less than 7 hours with $a_x \sin i \gtrsim 0.1$ lt-sec per 2 σ (Fig. 2).

The heliocentric pulse period derived from these measurements was 7.679190 ± 0.000051 (2 σ), which

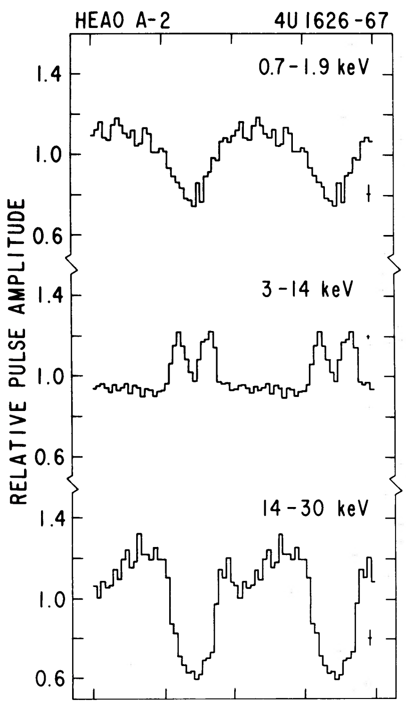

FIG. 1.—The master template obtained from these *HEAO* A-2 observations. One sigma uncertainties are shown. The amplitude has been normalized relative to the mean count rate above the background. The effective area of the HED in the 30–60 keV band is still of the order of ~50 cm² and the pulse was detected in this band. Although the statistics are not good quality, the pulse profile is similar in structure, amplitude, and phase to that seen in the 14–30 keV band.

when compared with the value 7.6806273 ± 0.0000005, obtained a year earlier by Joss *et al.*, yields a $\dot{P}/P$ of -1.87×10^{-4} yr^{-1}. This is consistent with that measured by Joss *et al.*

IV. AVERAGE SOURCE PROPERTIES

The average X-ray luminosity of 4U 1626−67 during the pointed observation was 2.9 (±0.3) × $10^{35}\, d_{\rm kpc}{}^2$ ergs s^{-1} between 0.7 and 60 keV. This result is similar to that observed with *Uhuru* (Giacconi *et al.* 1974) and *OSO 7* (Markert *et al.* 1979) in the 2–6 keV range, and also consistent with the result of Rappaport *et al.* (1977) in the 1–30 keV energy range of *SAS 3*. For 1 week in 1977 September we obtained scanning observations of 4U 1626−67. The average intensity was a third lower than that observed 6 months later and a factor ~2 variability was observed on time scales of hours. We cannot comment on the existence of the ~10^3 s quasi-periodic intensity oscillations discussed by Joss *et al.* because systematic aspect uncertainties during *HEAO 1* pointings can result in spurious effects with a similar time scale. The scanning data consist of ~2 minutes of observation every ~35 minutes and are also not relevant for the ~10^3 s time scale.

The phase-averaged spectrum between 0.7 and 60 keV is shown in Figure 3. Pravdo *et al.* (1978) discuss the method of spectral analysis. This spectrum is quite complex and can be fitted by a range of different models. Between 5 and 20 keV a power-law number index of ~0.4 adequately describes the data. Above 20 keV the spectrum falls off sharply. This is a canonical phase-averaged pulsar spectrum. Below 5 keV an additional thermal or blackbody continuum component is present in some models. The apparent column density of cool material in the line of sight (Brown and Gould 1970; Fireman 1974) is model-dependent but is always $\lesssim 4 \times 10^{21}$ H atoms cm^{-2}. A very broad line near 6.5 keV (FWHM $\gtrsim$ 2 keV) with 0.001–0.01 photons cm^{-2} s^{-1} significantly improves the model fits ($\Delta\chi_r{}^2 = 1$) and could indicate the presence of broadened iron line emission, which has been seen in other pulsars (Pravdo 1979, and references therein). However, the average spectrum is composed of radically varying constituent spectra, and thus the models for it may be misleading.

V. PULSE PHASE SPECTRA OF 4U 1626−67

Although the broad-band intensity pulses shown in Figure 1 are a representation of the spectral evolution, the pulse features (e.g., the rise time) are sensitively dependent on the chosen broad-band energy limits. In a model in which the X-ray emission is angle-dependent (the superstrong magnetic field model; e.g., Basko and Syunyaev 1975), there is more information in the energy distribution of photons at a particular phase than with the distribution of photons at a particular energy over all phases. Interpretation of the latter is

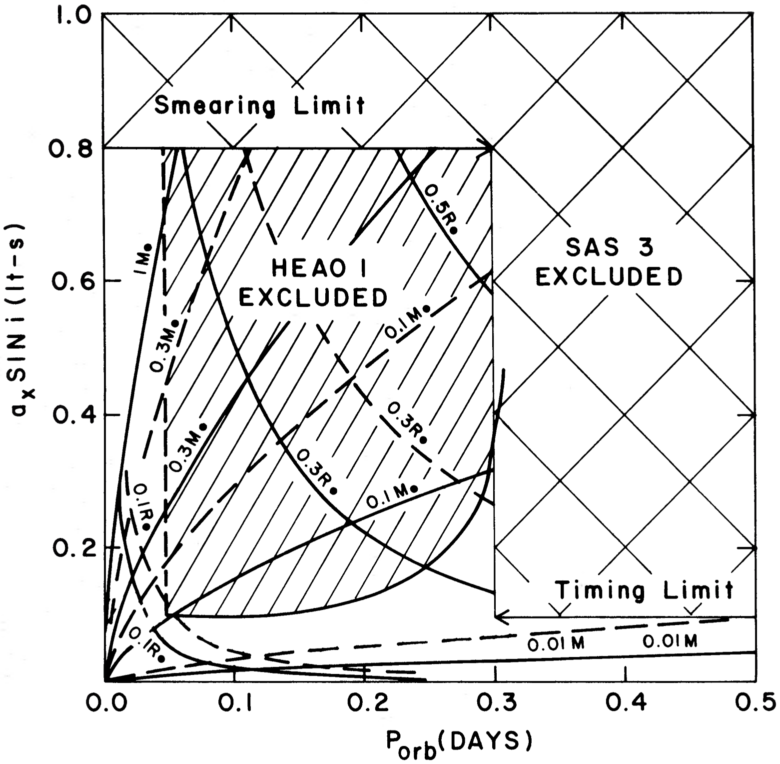

FIG. 2.—The new upper limit of allowed values of $a_x \sin i$ and P_{orb} obtained by *HEAO* A-2 superposed upon earlier *SAS 3* measurements (taken from Joss *et al.*). The solid and dashed lines are loci of the indicated values of the mass and radius of the companion for $M_x = 1.5\ M_\odot$ and $M_x = 0.5\ M_\odot$, respectively. Both assume $\sin i = 1$.

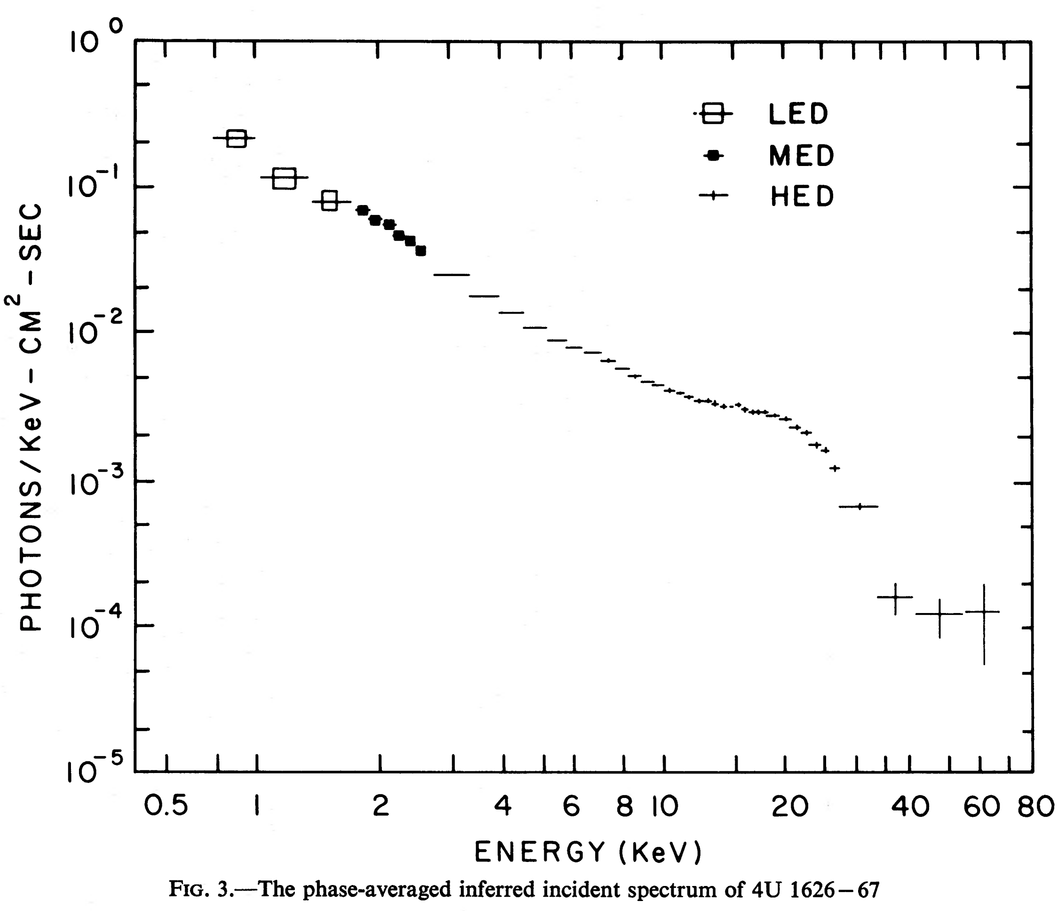

FIG. 3.—The phase-averaged inferred incident spectrum of 4U 1626−67

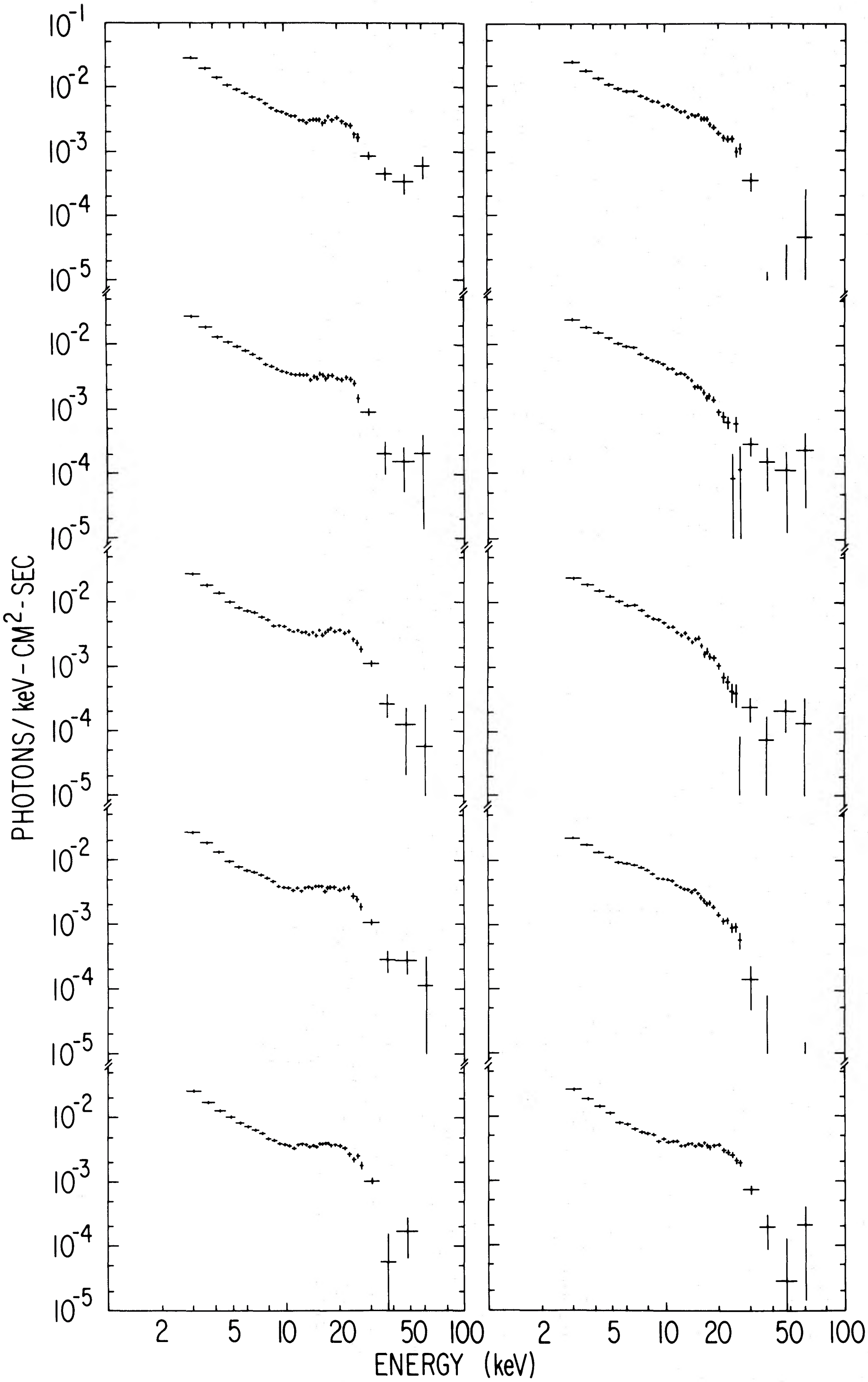

FIG. 4.—The spectrum of 4U 1626−67 as a function of pulse phase. Each spectrum corresponds to a successive 0.1 pulse phase starting in the upper left column and continuing down first the left and then the right column. The first spectrum begins at phase 0 as defined in the light curves in Fig. 1. Phase 0 corresponds to JD 2,443,596.5.

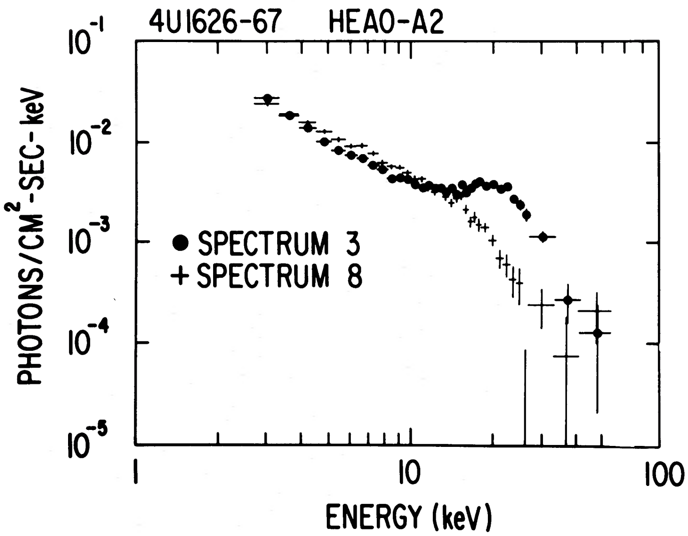

FIG. 5.—Superposition of spectra numbers 3 and 8

difficult, since one cannot distinguish the separate effects of energy-independent intensity changes (an overall pulse envelope) and spectral changes with pulse phase. We show in Figure 4 the evolution of the 4U 1626−67 spectrum across the pulse. Each spectrum, progressing down the left column and then the right column, is comprised of 0.1 phase. There is bimodal distribution among the 10 spectra displayed. Figure 5 shows spectra 3 and 8 superposed. Spectra 1–5 and 10 harden considerably with the addition of a continuum or broad emission feature centered near 19 keV. There is also a relative deficiency near 10 keV in these spectra. Again, as in the case of the phase-averaged spectrum, no simple continuum model can fit these data. We present examples of two possible classes of models.

A superposition of continuum components plus a high energy cutoff can describe the spectra in Figure 4. Table 1 lists relevant parameters (α, power-law index; E_c and E_F, cutoff parameters; T, temperature; and L, luminosity) for continuum models containing either a thin thermal bremsstrahlung or a blackbody component and a power-law continuum which is modified by a high energy cutoff factor of the form $\exp[-(E - E_c)/E_F]$. The variations of α, E_c, and E_F across the pulse are now familiar properties of other pulsar spectra, including Her X-1 (Pravdo *et al.* 1978) and 4U 0115+63 (Rose *et al.* 1979). There are both a spectrally hard pulse region and a soft pulse region, as well as a less dramatic spectral evolution within each region (Tables 1 and 2). A striking difference, however, between 4U 1626−67 and Her X-1 is that the spectrally hard section of the pulse has a duty cycle of 0.60 in the former compared with only 0.16 in the latter.

The power emitted in the possible low energy continuum components remains fairly constant over the pulse. For the blackbody model the temperature and luminosity imply a source radius of $\sim 1 \times 10^5\, d_{\rm kpc}$ cm.

TABLE 1

CONTINUUM MODELS

Spectrum ϕ	α	E_c*	E_F*	$T_{\rm TH}$*	$L_{\rm TH}$*	$T_{\rm BB}$*	$L_{\rm BB}$†	$L_{\rm tot}$†
0.	0.26	22.7	7.0	1.6	3.6	0.64	2.9	7.8
0.1	0.22	24.0	4.7	1.7	3.6	0.64	2.9	7.9
0.2	0.	22.9	5.8	1.6	2.4	0.65	3.1	7.3
0.3	0.	22.6	5.7	1.7	3.8	0.63	2.9	8.1
0.4	0.	21.7	5.4	1.7	3.8	0.63	2.9	8.1
0.5	0.30	15.7	7.7	2.1	3.2	0.65	2.4	8.2
0.6	0.50	13.3	7.6	1.8	2.3	0.68	2.8	8.4
0.7	0.56	15.1	6.6	1.7	2.2	0.68	2.5	8.4
0.8	0.48	14.9	7.8	1.5	1.8	0.65	1.7	8.7
0.9	0.40	23.7	4.6	1.6	3.3	0.63	2.7	8.1
Typical error	0.05	0.4	0.5	0.1	0.3	0.02	0.3	0.5

* Cutoff parameters E_c, E_F, and temperature for the thin thermal $T_{\rm TH}$ and blackbody $T_{\rm BB}$ models in keV.

† 2–10 keV luminosity in units of $10^{34}\, d_{\rm kpc}{}^2$ ergs s^{-1}.

TABLE 2

EMISSION FEATURE MODELS

	ONE-LINE MODEL			TWO-LINE MODEL					
SPECTRUM ϕ	T_{TH}*	E_L*	L_L†	T_{TH}*	E_{L1}*	L_{L1}†	E_{L2}*	L_{L2}*	L_{tot}†
0.	10.5	18.9	17.	4.6	18.2	19.	7.1	2.0	29.
0.1	11.2	19.3	17.	4.6	18.2	20.	6.3	1.9	26.
0.2	8.9	18.8	21.	7.1	19.1	21.	8.3	1.4	31.
0.3	8.8	18.5	22.	5.8	17.9	23.	7.7	0.4	31.
0.4	8.9	18.0	20.	5.8	17.2	22.	6.9	0.3	30.
0.5	10.0	9.2	14.	...	...	...	...	...	22.
0.6	11.7	8.1	6.1	...	...	...	...	...	18.
0.7	10.4	6.7	6.9	...	...	...	...	...	18.
0.8	11.0	6.2	11.	...	...	...	...	...	20.
0.9	9.3	17.5	18.	4.8	17.4	19.	8.5	1.2	28.
Typical error	2.6	2.7	0.8	0.6	1.0	0.8	0.8	0.2	1.8

* Thin thermal temperature T_{TH} and line energies E_L in keV.

† 2–60 keV luminosity in units of $10^{34}\, d_{kpc}^2$ ergs s^{-1}.

This radius is on the order of a neutron star size. A thermal source with this size would have an average density of $4 \times 10^{19}\, d_{kpc}$ cm^{-3} and could be ruled out because of the lack of observed low energy absorption or absorption edges. A radius greater than $\sim 10^9$ cm is indicated from the thermal model.

Another class of models contains broad emission features rather than multiple continuum components (Table 2). A single thin bremsstrahlung continuum with a broad (FWHM $\sim$ 15 keV) emission line can also describe these spectra. The centroid energy of this feature ranges from $\sim$19 keV to $\sim$7 keV, while the power in the line goes from $\sim$0.65 to $\sim$0.33 of the total power. If we assume that the lower energy feature is always present, then a two-line model marginally improves the fits for spectra 1–5 and 10. The temperature of the continuum remains fairly constant throughout the pulse but changes from $\sim$10 keV in the single-line model to $\sim$5 keV in the two-line model.

VI. DISCUSSION

We have found no evidence for any Doppler variation in the pulse phase of 4U 1626−67 that might result from orbital motion with periods between 1 and 7 hours. Combining this with the upper limit for periods between 7 hours and 300 days obtained by Joss *et al.* implies one of the following models: (1) the pulsar is an isolated neutron star accreting matter from an interstellar cloud; (2) it is part of a binary system whose inclination is low; or (3) the orbital period is less than 1 hour or greater than 300 days.

Joss *et al.* have discussed these possibilities in the light of their upper limits between 7 hours and 300 days. They discount the first two models as unlikely and propose a binary system with a period of the order of a few hours containing a neutron star accreting material from either a main-sequence dwarf or a low-mass white dwarf. For a white-dwarf companion with $\lesssim 0.2\, M_\odot$, $a_x \sin i$ would be $\lesssim 0.10$ lt-sec, which is at our measured limit. However, if the companion were a main-sequence M dwarf of mass $\sim 0.3\, M_\odot$ then our new upper limit indicates that it is of low inclination (i.e., $\lesssim 20°$). Thus the nature of this pulsar remains very much an open question.

Since a neutron star becomes a pulsar because of its superstrong magnetic field (e.g., Lamb, Pethick, and Pines 1973), it is natural to assume that the phase-dependent spectral characteristics are caused by magnetic effects. However, it is difficult to associate the magnetic field energy with a given spectral feature. In the case of 4U 1626−67 one might conclude that $B = 3 \times 10^{12}$ gauss because of the prominent feature at this energy. Or, since another feature may exist near 8 keV, the field strength could be half this value with the $\sim$19 keV feature the second harmonic. Alternatively, if the high energy cutoff is interpreted as cyclotron absorption (Pravdo *et al.* 1978), this implies a field strength of $\sim 6 \times 10^{12}$ gauss. This ambiguity results because no viable, comprehensive models that we are aware of now exist. Although there has been a considerable theoretical effort begun on this problem, in many cases important assumptions of the modeling may not have been justified. This particular situation probably requires use of the relativistically correct, strong field cross sections [with photon $E \sim (e\hbar/mc)B$] in a high temperature ($T > 20$ keV), optically thick plasma (Bussard 1978, and references therein).

It is interesting to note that the broad-band (2–60 keV) intensity of 4U 1626−67 does not appear to pulse. Over this energy range the narrow-band pulses destructively interfere. The number of photons remains constant, while the energy content of the pulse decreases by 30% with a duty cycle of 0.40 (see Table 2). To explain this we must devise a phase-dependent mechanism which conserves photon number while substantially changing photon energy. Compton scattering does both. However, the fact that the transition from hard to soft spectra occurs within 0.1 phase (Fig. 4) indicates that the mechanism cannot have performed the isotropization which accompanies normal Compton scatterings. Anisotropic Compton scattering in a strong magnetic field (Canuto, Lodenquai, and Ruderman 1971; Boldt *et al.* 1976) may therefore be an important part of the explanation.

There may be significance in a comparison of this source with Her X-1. In the 2–30 keV Her X-1 spectrum a single spectral form can adequately describe the spectrum over 84% of the pulse phase with only the normalization left as a free parameter (Pravdo *et al.* 1978). The normalization changes by a factor ~3, indicating a "background" component of emission which is spectrally but not spatially isotropic. A Compton scattering shell removed from the pulsar surface (Basko and Syunyaev 1976; McCray and Lamb 1976) with a suitable geometry could provide this emission and form the overall intensity envelope (Basko 1977). Another component of emission is viewed directly from the stellar surface in the Her X-1 hard X-ray "spectral pulse" (Pravdo *et al.* 1978). We suggest a connection between the presence of a background component in Her X-1 and the relatively small duty cycle of the spectral pulse. The Compton scattering shell could effectively shield the line of sight from most of the surface emission region. The 7 s pulsar has no background component and no broad-band intensity pulse. Perhaps in this case a Compton shell is either absent or too small to significantly shield any of the surface or to be the source of reflected X-rays. This shell is also thought to be the source of the intense soft X-ray ($T \sim 10^6$ K) flux from Her X-1 (Catura and Acton 1975; Shulman *et al.* 1975). Therefore we would not expect 4U 1626−67 to be a strong soft X-ray source. The spectral evidence is not yet complete (i.e., for $E < 0.7$ keV) but does tend to support this final point.

The spectra of 4U 1626−67 are so complex that at the present time no firm conclusions about the emitting regions can be made. Detailed modeling of the spectral changes across the pulse is required for further progress. However, these spectra are only the most extreme example of common X-ray pulsar phenomena. Recently features have been detected in the X-ray spectra of two pulsars. These have been interpreted as an emission line in Her X-1 (Trümper *et al.* 1978) and an absorption line in 4U 0115+63 (Wheaton *et al.* 1978), originating in the superstrong magnetic field ($>10^{12}$ gauss) at the surface of neutron stars. However, in these analyses the assumption was made that a nonvarying emission component exists and is found in the pulse intensity minimum. In both cases cited above the intensity minimum of the pulse was used as a background spectrum for the intensity maximum to obtain a "pulsed spectrum," although Trümper *et al.* obtained similar results of lower statistical significance using off-source background. Using the same procedure for the spectra shown in Figure 5 would result in dramatic nonphysical spectral features. Rose *et al.* (1979) have discussed similar effects in the spectrum of 4U 0115+63 in which a *narrow* feature can appear in the net spectrum. We conclude that in general, the nonvarying component cannot be eliminated by this method without the danger of subtracting one part of the pulsed emission from another and thereby creating spurious features.

We acknowledge useful discussions with F. K. Lamb, D. Q. Lamb, R. Lamb, P. L. Lamb, and J. Cash.

REFERENCES

Basko, M. M. 1977, *Astr. Zh.*, **54**, 1050 (English transl. in *Soviet Astr.—AJ*, **21**, 595).
Basko, M. M., and Syunyaev, R. A. 1975, *Astr. Ap.*, **42**, 311.
———. 1976, *M.N.R.A.S.*, **175**, 395.
Boldt, E. A., Holt, S. S., Rothschild, R. E., and Serlemitsos, P. J. 1976, *Astr. Ap.*, **50**, 161.
Brown, R. L., and Gould, R. J. 1970, *Phys. Rev. D*, **1**, 2252.
Bussard, R. W. 1978, Ph.D. thesis, University of Maryland.
Canuto, V., Lodenquai, J., and Ruderman, J. 1971, *Phys. Rev. D*, **3**, 2303.
Catura, R. C., and Acton, L. W. 1975, *Ap. J.* (*Letters*), **202**, L5.
Fireman, E. L. 1974, *Ap. J.*, **187**, 57.
Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Koch, D., and Tananbaum, H. 1974, *Ap. J. Suppl.*, **27**, 37.
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., Pethick, C. J., and Pines, D. 1973, *Ap. J.*, **184**, 271.
Markert, T. H., *et al.* 1979, *Ap. J. Suppl.*, **39**, 573.
McClintock, J. E., Canizares, C. R., Bradt, H. V., Doxsey, R. E., and Jernigan, J. G. 1977, *Nature*, **270**, 320.
McCray, R., and Lamb, F. K. 1976, *Ap. J.* (*Letters*), **204**, L175.
Pravdo, S. H. 1979, in *X-Ray Astronomy*, ed. L. P. Peterson and W. Baity (Oxford: Pergamon), in press.
Pravdo, S. H., Bussard, R. W., Becker, R. H., Boldt, E. A., Holt, S. S., and Serlemitsos, P. J. 1978, *Ap. J.*, **225**, 988.
Rappaport, S., Markert, T., Li, F. K., Clark, G. W., Jernigan, J. G., and McClintock, J. E. 1977, *Ap. J.* (*Letters*), **217**, L29.
Rose, L. A., Pravdo, S. H., Kaluzienski, L. J., Marshall, F. E., Holt, S. S., Boldt, E. A., Rothschild, R. E., and Serlemitsos, P. J. 1978, *Bull. AAS*, **10**, 506.
———. 1979, *Ap. J.*, submitted.
Rothschild, R., *et al.* 1978, NASA TM 79574 (*Space Sci. Instr.*, submitted).
Schulman, S., Friedman, H., Fritz, G., Henry, R. C., and Yentis, D. J. 1975, *Ap. J.* (*Letters*), **199**, L101.
Trümper, J., Pietsch, W., Reppis, C., Voges, W., Staubert, R., and Kendziorra, E. 1978, *Ap. J.* (*Letters*), **219**, L105.
Ulmer, M. P. 1975, *Ap. J.*, **196**, 827.
Wheaton, W., *et al.* 1978, *Bull. AAS*, **10**, 446.

E. A. Boldt, S. S. Holt, S. H. Pravdo, P. J. Serlemitsos, J. H. Swank, A. E. Szymkowiak, and N. E. White: Code 661, Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771

G. Garmire and I. Tuohy: California Institute of Technology, Pasadena, CA 91125