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EXOSAT AND *EINSTEIN* OBSERVATIONS OF THE X-RAY PULSAR 4U 1145−619

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ABSTRACT

Results are presented of several *Einstein* and *EXOSAT* X-ray observations of 4U 1145−619, an X-ray pulsar orbiting the Be star HD 102567/Hen 715 with marked transient behavior. Pulse-timing analysis of data from imaging instruments on both missions was performed using a period-folding technique, which showed an interesting variation of the light curve shape. During observations at periastron, where the source was predictably brighter, a strong variability was observed on the time scale of several thousand seconds. The global X-ray picture presented can be interpreted in the context of an eccentric binary system with variable accretion, but especially the low-energy *EXOSAT* channel multiplier array pulsed light curve raises new questions on the detailed accretion geometry.

Subject headings: X-rays: binaries — X-rays: bursts

I. INTRODUCTION

The puzzle of the two X-ray pulsations with similar periods (291 and 297 s) discovered by the *Ariel 5* satellite from the vicinity of the *Uhuru* source 4U 1145−619 (White *et al.* 1978) could only be solved two years later, thanks to the greatly improved angular resolution of the *Einstein Observatory* (Giacconi *et al.* 1979). Using an imaging proportional counter observation, Lamb *et al.* (1980) could resolve the *Uhuru* source into two sources separated by 15′ and characterized by two different periodicities. The fainter source, 1E 1145.1−6141, has the longer period, and it is very probably a magnetized neutron star in a massive binary system (Illovaisky, Chevalier, and Moch 1982; Densham and Charles 1982). Its distance is ~ 8 kpc, if its optical identification is correct.

We concentrate on the brighter source, 4U 1145−619, which has been optically identified with the 9th mag B star Hen 715 (Dower *et al.* 1978, following the original proposals of Sofia 1974 and Jones, Chetin, and Liller 1974) at an estimated distance of ~ 1.5 kpc. The X-ray flux from 4U 1145−619 is highly variable and shows outbursts recurring with a periodicity of ~ 6 months (Watson, Warwick, and Ricketts 1981). During the outbursts, which last several days, the X-ray luminosity usually increases by a factor of ~ 5 from the steady level of $\sim 10^{35}$ ergs s^{-1} (in the 2–10 keV energy range, assuming $d = 1.5$ kpc). The X-ray periodicity has been confirmed by Priedhorsky and Terrell (1983) and more recently by *EXOSAT* medium energy (ME) observations (Warwick, Watson, and Willingale 1985), leading to the best orbital period value of 186.5 days. Detailed UV and optical measurements of HD 102567/Hen 715 have been reported by Hammerschlag-Hensberge *et al.* (1980) and by Bianchi and Bernacca (1980), leading to evidence for a main-sequence, B star with emission lines and equatorial rotational velocity $v \sin i = 290$ km s^{-1}.

The optical and X-ray characteristics of 4U 1145−619 thus indicate that this source may belong to the class of long-period binaries in which a neutron star is orbiting a rapidly rotating B emission star (Maraschi, Treves, and van den Heuvel 1976). Here we present the results of an analysis performed on the pulsar flux, period, and light curve using all the available data obtained from 4U 1145−619 by the imaging instruments of the *EXOSAT* and *Einstein* observatories.

II. DATA ANALYSIS

Table 1 gives a journal of the observations analyzed here: four *Einstein Observatory* imaging proportional counter (IPC) and high resolution imager (HRI) observations and three *EXOSAT* low energy (LE) telescope observations. Parts of the data collected by the *Einstein Observatory* have already been published: the observation IPC 3942, in which the new pulsar 1E 1145.1−6141 was discovered by Lamb *et al.* (1980) and the HRI fields used by Hutchings, Crampton, and Cowley (1981) to precisely determine the positions of the two X-ray pulsars. For completeness we have also reanalyzed those data which are now available in the reprocessed version (see Harnden *et al.* 1984).

a) Einstein Observatory Data

In the analysis of the IPC observation of 1979 July (IPC 3942) we have used the method described in Bignami, Caraveo, and Paul (1984) to select the set of photons to include in the pulse-timing analysis. The best signal-to-noise ratio (S/N) was obtained taking all the counts falling within a radius of 15 pixels (2′) from the X-ray position of 4U 1145−619 and corresponding to the energy range 0.2–4.5 keV. The 344 counts obtained in this way were folded in 10 phase bins, varying the trial period from 200 to 400 s in steps of 2 s. The resulting light curves were compared to the one expected from a constant source using a standard χ^2 test. The maximum value of the reduced χ^2 (12.95 over 9 degrees of freedom [d.o.f.], corresponding to a chance occurrence probability lower than 10^{-8}), which we assume to correspond to the best estimate of the true pulse period, was obtained for a period of 290.0 ± 2.0 s. This value of the period, the shape of the light curve (Fig. 1) and the distribution of the χ^2 value versus trial period are completely in agreement with those previously derived by Lamb *et al.* (1980).

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TABLE 1

JOURNAL OF OBSERVATIONS

Observation	Date	JD (+2,400,000.5)	Orbital Phase	Exposure Time (s)	Useful Time (s)
IPC 3942	1979 Jul 13	44,067	0.27	1884	1638
IPC 7718	1980 Aug 24	44,475	0.45	11715	5284
HRI 7570	1980 Feb 3	44,272	0.38	10117	7317
HRI 4957	1980 Feb 3	44,272	0.38	11627	6944
CMA D177	1983 Jun 26	45,511	0.01	24300	13599
CMA D188	1983 Jul 7	45,522	0.06	11820	11506
CMA D43	1984 Feb 12	45,742	0.24	20220	19907

The percentage of the source pulsed flux in our analysis is 42% $\pm$ 8%. As shown in Fig. 1, no differences are seen in the pulsed fraction or pulse shape when the data are divided into the two energy ranges (0.16–1.4 and 1.4–4.5 keV).

At the time of the I3942 observation, the detected source flux was $0.86 \pm 0.20 \times 10^{-11}$ ergs cm^{-2} s^{-1} in the energy range 0.2–2.0 keV (chosen in order to allow direct comparison with the *EXOSAT* data). We have computed this flux, and those quoted below, assuming a power-law spectral shape with energy index $\alpha = 0.65$ and a column density $N_H = 3 \times 10^{21}$ cm^{-2}. These spectral parameters, consistent with those proposed by White *et al.* (1980) and with the 1.5 kpc proposed distance to the optical counterpart star Hen 715, are in accord with those derived from a rough IPC spectral analysis.

During the $\sim$1900 s observation, no significant flux variations (at the 3 σ level) were observed on time scales longer than the pulse period.

4U 1145−619 was reobserved with the IPC on 1980 August 24 (IPC 7718). About 3500 s of the observation were rejected in the standard data reduction because the satellite pointing direction was not known with the required precision. Since we are not interested in good positional accuracy, but rather in collecting the largest possible number of photons, we included in our analysis also the data intervals characterized by a bad aspect solution.

An examination of the resulting IPC image showed that, even if the radial distribution of counts from 4U 1145−619 was not compatible with the instrumental point-spread function, the great majority of the source counts were within a circle with a radius of $\sim 3'$. With the inclusion of bad aspect data we could perform the temporal analysis on $\sim$1250 counts (instead of only 750). Periods from 280 to 300 s were considered with steps of 0.25 s and using the method described above to determine the period value. A maximum reduced $\chi^2 = 12.50$ (over 9 d.o.f., corresponding to a very low [$<10^{-8}$] chance probability) was obtained, for a period of 291.50 ± 1.0 s. The resulting light curve is shown in Figure 2. It presents a single peak with a pulsed fraction of 30% $\pm$ 5% and a pulse shape possibly slightly different from the one observed in IPC 3942 (see Fig. 1).

The total flux at the time of the I7718 observation was $0.60 \pm 0.05 \times 10^{-11}$ ergs cm^{-2} s^{-1}, adopting the same assumptions as before. As for I3942, no significant (>3 σ) flux variations were present on time scales longer than the pulse period during this 11,700 s observation.

The two HRI fields (HRI 4957 and HRI 7570) were pointed at the pulsars 4U 1145−619 and 1E 1145.1−6141 respectively, but both sources were visible in the observation HRI 7570. The latter observation consisted of $\sim$7000 s almost immediately followed by the HRI 4957 observation. Folding the counts

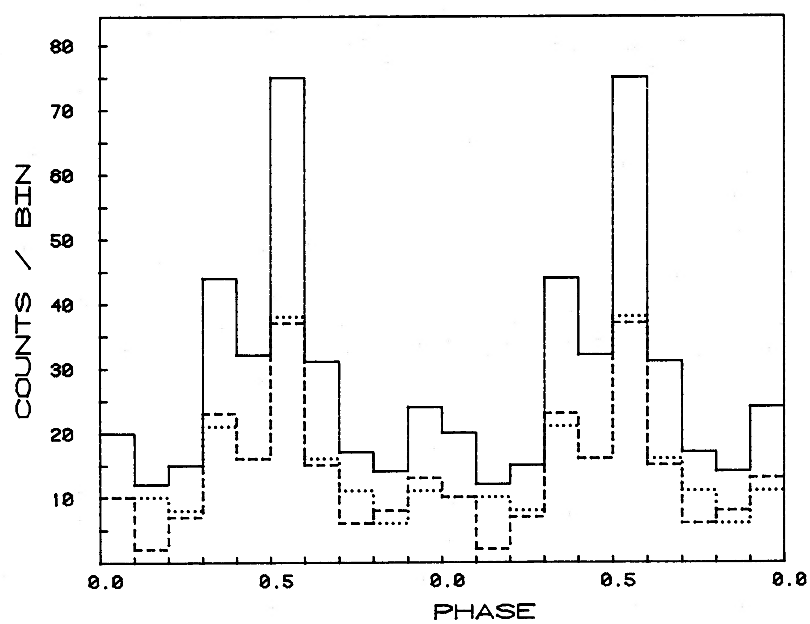

FIG. 1.—*Einstein Observatory* IPC 3942 observation light curves folded modulo $P = 290.0$ s. *Solid line:* all energies, including 284 photons, and yielding a reduced $\chi^2 = 12.95$ (9 d.o.f.). *Dashed line:* same, for the energy range 0.16–1.4 keV. *Dotted line:* same, for 1.4–4.5 keV.

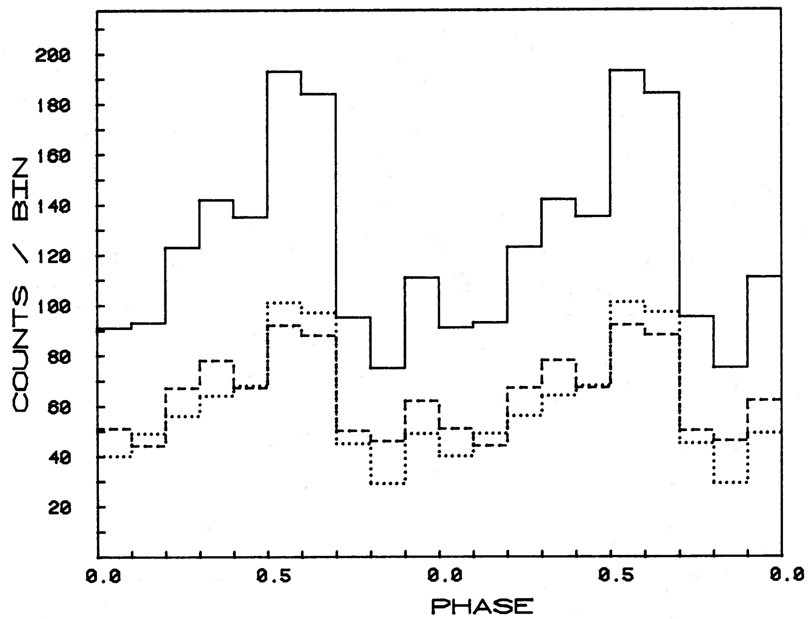

FIG. 2.—IPC 7718 observation, $P = 291.5$ s. *Solid line:* all energies, 1250 photons, $\chi^2 = 12.50$. *Dashed and dotted lines:* as in Fig. 1.

from HRI 4957 and HRI 7570 together, we could analyze 370 photons spanning a time interval of ~ 6 hr. We examined periods between 280 and 300 s with a step of 0.1 s. Figure 3*a* shows the result of the χ^2 versus period search. A peak in the reduced χ^2 distribution appears with a maximum of 4.27 (chance occurrence probability of 10^{-5}) for $P = 289.6 \pm 2.0$ s; however, the corresponding light curve (Fig. 3*b*) shows strong fluctuations rather than the well-defined peak of the IPC signal. Although the data of Figure 3*b* do not, by themselves, appear convincing, the sharp maximum of Figure 3*a*, located near the (previously known) value of the period, suggests that the pulsation is also present in the HRI data, albeit at a lower significance level. The range of periods (280–300 s) searched, and the absence of other peaks above 3 σ, both in the source and in the background data, lend support to the credibility of the periodicity detection in the HRI data as well.

b) *EXOSAT* Data

The *EXOSAT* satellite was pointed toward 4U 1145−619 on 1983 June 26 (day 177) and July 7 (day 188) and 1984 February 12 (day 43) (see Table 1). A preliminary analysis of the ME data has recently been presented by Warwick, Watson, and Willingale (1985). In what follows, we use only data from the LE imaging telescopes with the channel multiplier array (CMA) at their focus. An image of the CMA field for day 43 (D43) has already been given by Bignami *et al.* (1986) in the context of the discussion of a nearby supernova remnant, 1E 1149.4−6209. The *EXOSAT* fields of the region show more sources than the *Einstein* ones; most of them are easily identifiable with field stars, which are seen due to the CMA sensitivity to UV radiation through the thin (3000 Å) Lexan filter constantly used for the observations. In the case of 4U 1145−619 this was checked, and the possible UV contribution from Hen 715 was seen to be small.

The usual S/N optimization procedure was applied to select CMA source photons for the temporal analysis, and Figure 4 shows the results for D177. The pulsation effect is clearly seen, with a maximum reduced χ^2 of 7.5 (chance probability $< 10^{-7}$), at 291.1 ± 1.0 s. The light curve is characterized in this case by two peaks, separated by 0.4 of phase, contrary to the IPC single-peaked light curves. As apparent, the pulsed fraction is in this case greater, i.e., $64\% \pm 8\%$. The total flux from the source, averaged over the $\sim 24{,}000$ s observation, is $4.97 \pm 0.23 \times 10^{-11}$ ergs cm^{-2} s^{-1}, in the 0.2–2.0 keV interval. A significant variability of the flux is present within this observation: Figure 5 shows the count rate time profile, where two sudden increases in flux, followed by slower decays, are visible. In both cases the rise time is shorter than 1000 s. Similar variability has been reported by Warwick, Watson, and Willingale (1985) for the simultaneous ME data. No variation of the light curve shape and of the pulsed fraction were found during the outbursts. The average source flux during the outburst is $10.52 \pm 0.54 \times 10^{-11}$ ergs cm^{-2} s^{-1}, while the quiescent source flux is $2.76 \pm 0.23 \times 10^{-11}$ ergs cm^{-2} s^{-1}.

For the D188 (1983) and the D43 (1984) observations, no pulse-timing analysis could be performed. This was due to the configuration of the on-board computer during D188, and to the very limited statistics available for D43. It has been possible, however, to compute the 0.2–2.0 keV flux for both observations, yielding $2.28 \pm 0.16 \times 10^{-11}$ ergs cm^{-2} s^{-1} and $0.62 \pm 0.09 \times 10^{-11}$ ergs cm^{-2} s^{-1}, for D188 and D43 respectively. We note that the D188 source flux level is comparable to the quiescent flux measured ~ 10 days before. No significant ($> 3\ \sigma$) flux variability on time scales longer than the pulse period was found within the 12,000 s D188 data.

All the above mentioned results are summarized in Table 2, where the source flux, the pulse period, and the light curve characteristics are shown for each observation as a function of the orbital phase.

III. DISCUSSION AND CONCLUSIONS

The X-ray observational data summarized in Table 2 present a picture which is broadly consistent with the accepted model of the 4U 1145−619/Hen 715 system, namely that of a Be star losing mass to a neutron star in an eccentric orbit. This is also apparent in Figure 6, which shows all the CMA-IPC

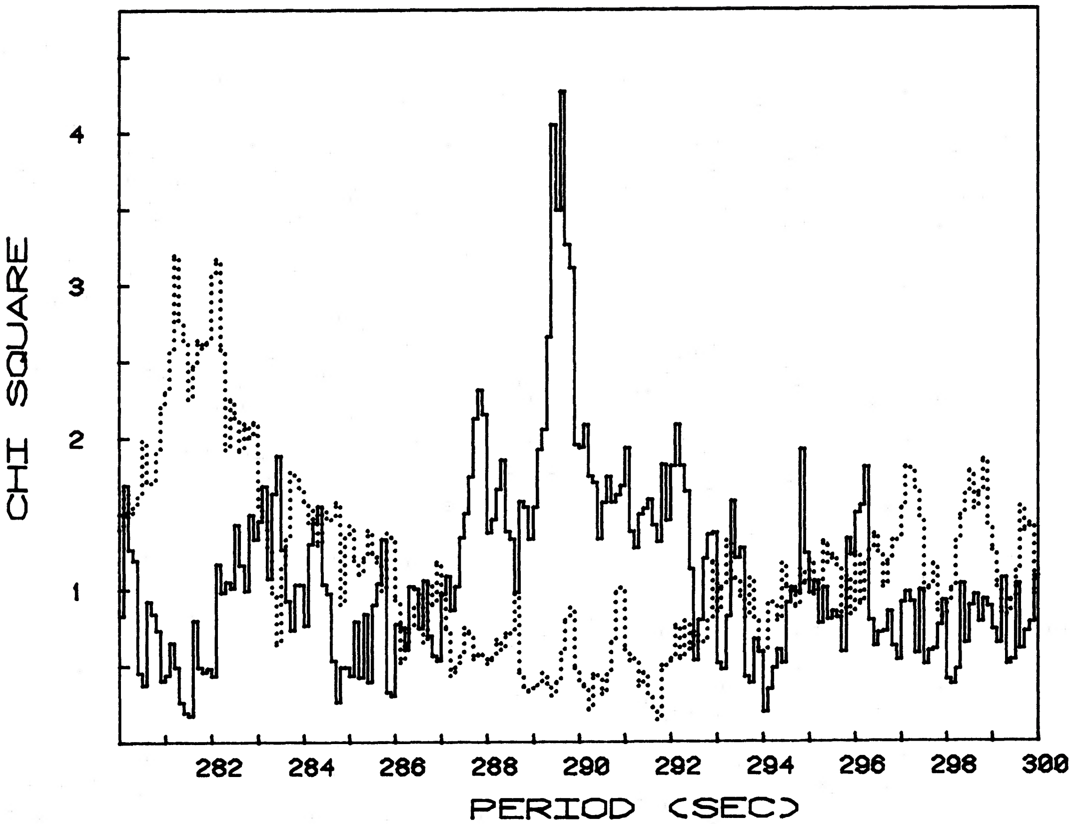

FIG. 3*a*

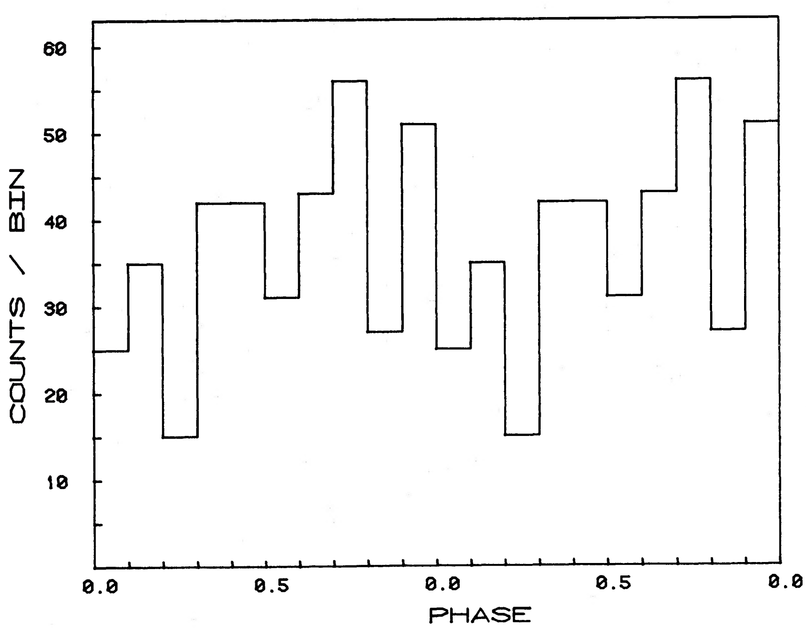

FIG. 3*b*

FIG. 3.—HRI data, including H4975 and H7570. (*a*) Distribution of reduced χ^2 vs. period, showing a maximum at 289.6 ± 2.0 s ($\chi^2 = 4.27$). *Dotted line*, background counts. (*b*) Light curve of the 370 photons folded at the best period.

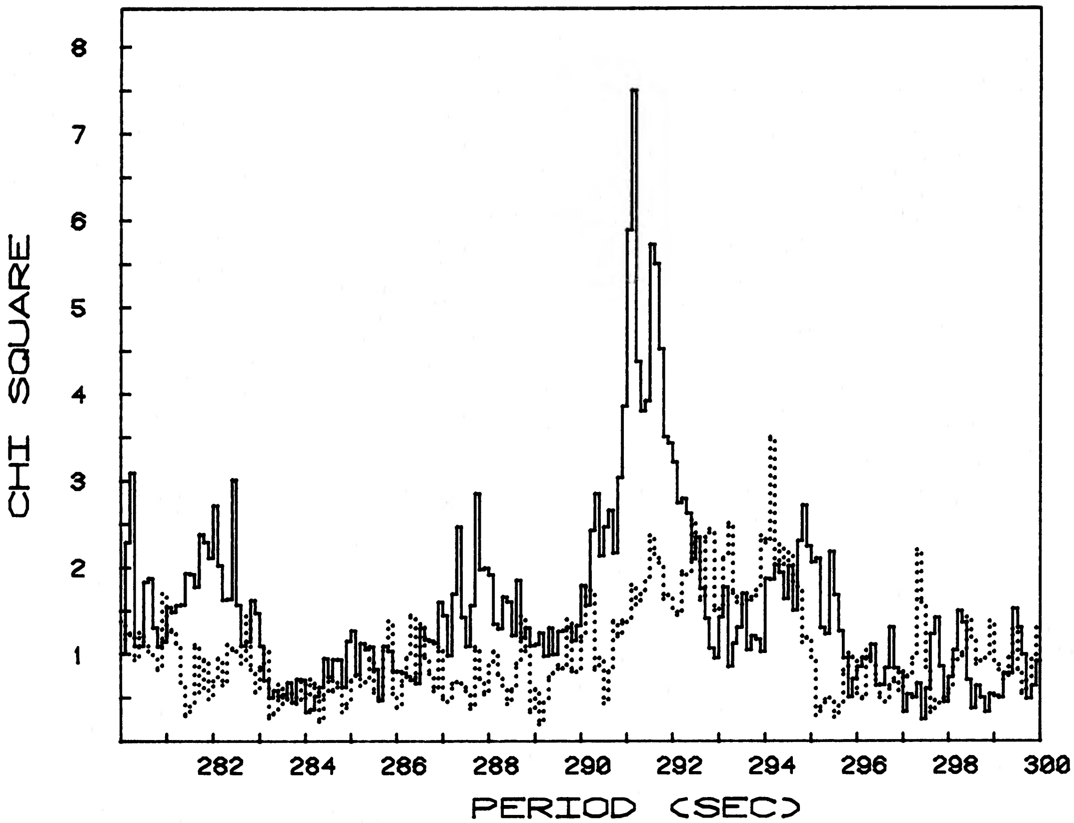

FIG. 4*a*

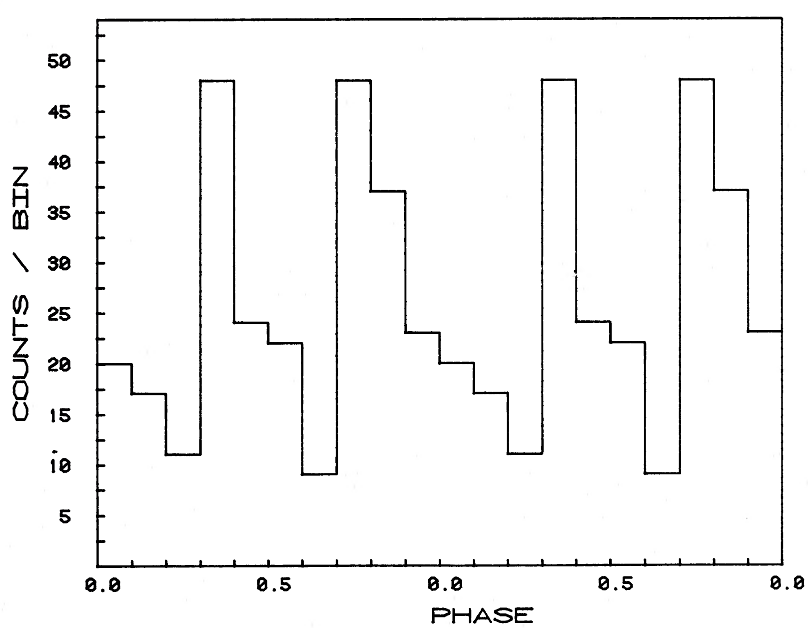

FIG. 4*b*

FIG. 4.—Period search in the *EXOSAT* CMA D177 data. (*a*) distribution of reduced χ^2 vs. period, showing a maximum $\chi^2 = 7.50$ at $P = 291.1 \pm 1.0$ s. *Dotted line*, background counts. (*b*) Light curve at the best-period value; two peaks seem now to be present, in contrast with the IPC case.

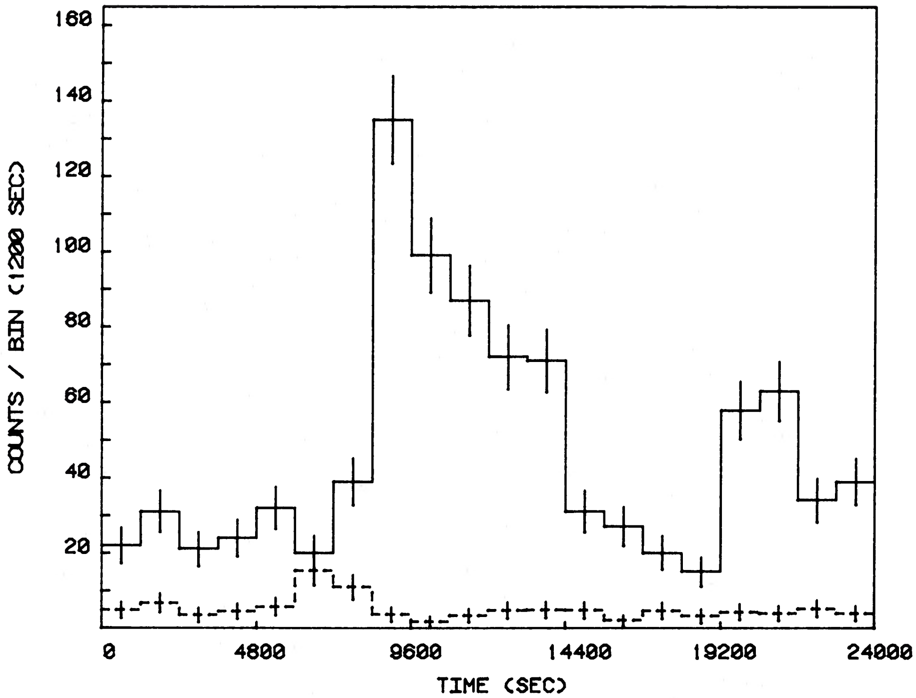

FIG. 5.—Time profile of CMA count rate during the D177 observation. The source flux (*solid line*) is seen to undergo flares on time scales of several thousand seconds. *Dashed line:* background counts.

(0.2–2.0 keV) fluxes as a function of the orbital phase, and where the increase in source activity at periastron (i.e., around phase 0) is apparent. Such an increase is consistent with that of a factor of 5–10 reported as normal by Watson, Warwick, and Ricketts (1981), using data on more periastron passages; however, we do not find evidence for the dramatic L_{max}/L_{min} increase of ~ 250 reported by Stella, White, and Rosner (1986), and presumably based on the somewhat suspicious outbursts reported by Jernigan *et al.* (1978; see Priedhorsky and Terrell 1983). On the other hand, it is interesting to observe that, using only *EXOSAT* data and comparing our LE CMA (0.2–2.0 keV) data to the simultaneous ME ones (2–10 keV) of Warwick, Watson, and Willingale (1985), our increase of a factor of 5 is significantly smaller than theirs, which is $\gtrsim 10$. This is probably best interpreted on the basis of a hardening of the source spectrum at higher accretion regimes, a behavior frequently observed in accreting binaries; naturally the problem could be complicated by a phase-dependent absorption of the low-energy component, for which we cannot offer experimental evidence at this time, but which could no doubt be tested, using, e.g., further ME data at different phases.

Turning now to the irregular, flaring behavior observed within CMA D177 (Fig. 5), again this is to be expected in a system where accretion is driven by stellar wind capture. The system is too widely separated for the donor star to fill its Roche lobe and thus for a disk to form (see, e.g., White, Swank, and Holt, 1983), also owing to a measured wind velocity of ~ 1000 km s^{-1} (Hammerschlag-Hensberge *et al.* 1980). Irregularities or "blobs" in the wind can certainly produce the observed flaring; on the other hand, a similar effect could be mimicked by the passage of the neutron star near the periastron through a generally thicker equatorial region surrounding the rapidly rotating Be star. While in fact both effects could be present, of greater interest could be the marked asymmetry present in the peak of Figure 5, with a rise time of about $\frac{1}{3}$ to $\frac{1}{4}$ of the decay time. A possible interpretation could be linked to compression of the accreting material in the bow shock of the neutron star, followed by the passage of more diluted "downstream" material.

Altogether, the data on the time-averaged fluxes from 4U 1145−619 lead to conclusions in agreement with the statement that this source is one of "the best approximations that we will find to spherically symmetric accretion in binary systems" (White, Swank, and Holt 1983).

From the data presented in Figures 1, 2, and 4*b*, there emerges a new aspect of the pulsating behavior of this source.

TABLE 2

SUMMARY OF RESULTS

Observation	Phase	Flux (0.2–2.0 keV) (10^{-11} ergs cm^{-2} s^{-1})	Variable?	Period (s)	Pulsed Fraction	Light Curve
CMA D177	0.01	4.97 ± 0.23	Yes	291.1 ± 1.0	64% ± 8%	Two peaks
CMA D188	0.06	2.28 ± 0.16	No	...	...	...
CMA D43	0.24	0.62 ± 0.01	No	...	...	...
IPC 3942	0.27	0.86 ± 0.20	No	290.0 ± 2.0	42 ± 8	One peak
HRI 4957, 7570 ..	0.38	0.51 ± 0.03	No	289.6 ± 2.0	...	Unclear
IPC 7718	0.45	0.60 ± 0.05	No	291.5 ± 1.0	30 ± 5	One peak

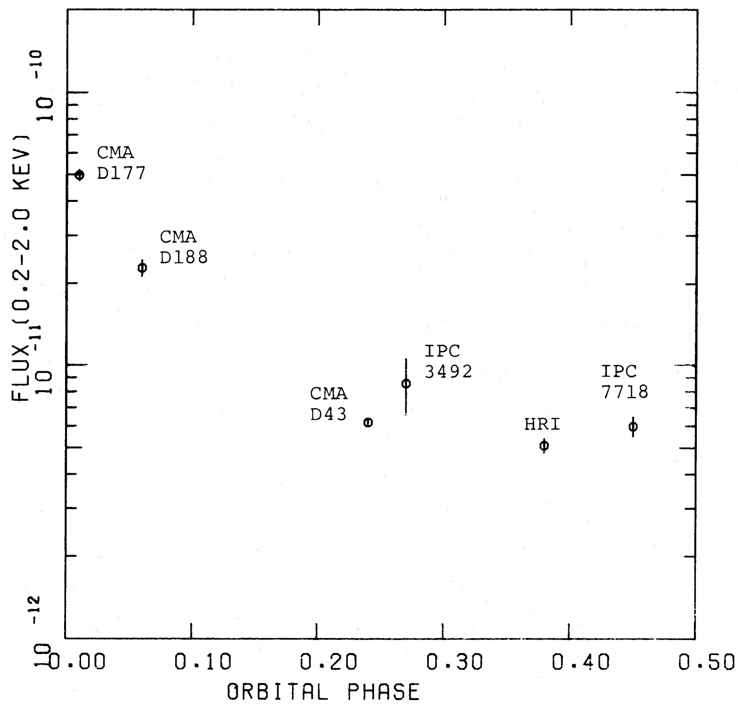

FIG. 6.—A compilation of all the soft (0.2–2.0 keV) X-ray fluxes from 4U 1145−619, as a function of the 186.5 day orbital phase, using the ephemeris reported by Warwick, Watson, and Willingale (1985). The fluxes, in ergs cm^{-2} s^{-1}, are computed assuming a power-law energy spectrum with $\alpha = 0.65$ and $N_H = 3 \times 10^{21}$ cm^{-2}.

The IPC data show evidence for a single-peaked light curve in both observations (at orbital phases 0.27 and 0.45), consistent with the shape observed by White *et al.* (1980) at an orbital phase of 0.27 and 0.41. No difference appears when the data are divided into higher and lower energy regions, so that a simple energy dependence cannot explain the clearly two-peaked shape of the CMA D177 light curve. The latter observation, on the other hand, was taken at orbital phase 0.01, with a much enhanced accretion, where a multipeaked light curve, especially at lower energies, is expected, e.g., in the model of Elsner and Lamb (1976). Such an effect could then be due to the presence of multipole components of the magnetic field near the surface of the neutron star and would be more felt when movement through a higher density region compresses the pulsar magnetosphere. In principle, *EXOSAT* ME (2–10 keV) data also exist for the same observation and would thus be of interest in checking the depth and shape of the pulsar modulation.

On the pulsar period itself, our period determination accuracy is limited by the short duration of each observation, yielding values in agreement (see Table 2) with previous data, but not sufficient to claim a systematic variation with orbital phase, or, in fact, any variation at all. Moreover, even if the small period variations observed were real, they could be due to localized variations in the accretion rate, with consequent variations in the transfer of angular momentum.

Finally, the 4U 1145−619/Hen 715 system lies on the correlation curve existing between pulsar and orbital periods for X-ray binaries containing a Be star, as first suggested by Corbet (1984). This, however, does not per se provide further clues for the understanding of the system; more data are needed, especially on the long-term optical behavior.

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