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Reprocessed UV pulses from the binary companions of X-ray pulsars*

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Abstract. A search for reprocessed X-rays causing UV pulsations in the companion stars to X-ray pulsars was carried out in a 200 Å wide bandpass centered at 1450 Å using the High Speed Photometer on the Hubble Space Telescope. We observed the systems A0535+26 = HD245770, 4U0900-40 (Vela XR-1) = HD77581, A1118-61 = He3-640, and 4U1145-619 = HD102567. We confirm the existence of reprocessed X-rays reported in 4U0900-40 by Boroson et al. (1996) and give upper limits on the pulsed fraction in our UV bandpass present in the other systems. Archival IUE spectra are consistent with the finding of Boroson et al. that the UV radiation from HD77581 is emitted primarily in resonance emission lines from multiply ionized metals. The existence of two different pulse frequencies (UV and X-ray) in an X-ray binary system makes it dynamically equivalent to a double-lined spectroscopic binary. If the UV pulses are emitted from a site in the primary's outer atmosphere rather than its stellar wind, then the mass of the neutron star can be derived from the orbital phase dependence of the two frequencies.

Key words: binaries: close – stars: individual: HD 77581 – stars: neutron – pulsars: individual: 4U 0900-40 – ultraviolet: stars – X-rays: stars

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1. Introduction

X-ray binary systems often contain neutron stars (NS) possessing strong magnetic fields that ultimately channel the mass accreted from the companion star (via a stellar wind or Roche lobe overflow) onto the regions surrounding the NS magnetic poles. The radiation pattern emitted is strongly directional, with the rotating NS often appearing to observers as an X-ray pulsar. Shortly after the discovery of X-ray pulsars in binary systems, it was realized that the illumination of the hemisphere facing the NS by the X-ray pulses should lead to pulsed radiation from the companion in the UV and visible (Basko & Sunyaev 1973; Avni & Bahcall 1974). The X-rays are absorbed in the upper levels of the companion star's atmosphere and their energy is expected to be reradiated on a timescale of seconds (Dahab 1974; Alme & Wilson 1974). The resulting pulses will have a frequency different from that of the X-ray pulses emitted simultaneously, being Doppler shifted by an amount corresponding to the relative velocity of the pulsar and the emitting region as projected on the line of sight (Groth 1974). The two different pulse frequencies in the system make it the dynamical equivalent of a double-lined spectroscopic binary, and the mass of the NS star can be derived from the orbital phase dependence of the two frequencies (Middleditch & Nelson 1976).

A well-determined range of NS masses is needed to constrain the equation of state of NS matter and to indicate the evolutionary tracks of stars that form NS (van Kerkwijk, van Paradijs, & Zuiderwijk 1995a). The detection of reprocessed optical pulses from binary systems containing X-ray pulsars offers the possibility, at least in theory, of determining masses for several different neutron stars accurately enough to guide the theoretical analyses of these problems.

Table 1. Journal of observations

System	Start JD 2 440 000+	Duration (s)	F145M Mean Counting Rate s^{-1}	Binary Phase[a]
A0535+26	8993.1709	2617	146 ± 0.2	0.34
4U0900-40	8993.7815	2880	714 ± 0.5	0.921–0.926
A1118-61	8986.0671	2880	3.1 ± 0.03	0.05:
4U1145-619	9207.8250	2880	1061 ± 0.6	0.84

[a] See text for explanation

Optical pulses were first detected from HZ Her, the companion star to Her X-1, by Davidsen et al. (1972). A complete analysis of the Her X-1 system based on the different periods of X-ray and reprocessed pulses as a function of orbital phase was carried out by Middleditch and Nelson (1976), who found a mass of 1.30 ± 0.14 $M_\odot$ for the NS (but cf. Chester [1978], who found 1.2 ± 0.4 $M_\odot$ from a different analysis of the same data). Middleditch (1983) estimates that a precision of $\pm$ 0.1 $M_\odot$ can be attained with this method. 4U1626-67 is the only other X-ray pulsar system from which optical pulses have been detected (Ilovaisky, Motch, & Chevalier 1978; McClintock et al. 1980; Peterson et al. 1980; Middleditch et al. 1981), although the location from which the reprocessed pulses from 4U1626-67 originate remains uncertain. The lack of observable Doppler shifts in the period of the optical pulses prevents 4U1626-67 from being treated as a double-lined spectroscopic binary. Systems in which reprocessed pulses have been sought without success in the visible and UV include A0535+26 = HD245770, 4U0900-40 (Vela XR-1) = HD77581, and 4U1145-619 = HD102567 (Margon et al. 1977; Payne & Coe 1987). Steiner (1977) reported that the flux in the Hα line of HD77581 was modulated with 2% amplitude at the frequency of the X-ray pulses in the system, but because this modulation existed even during the phases of X-ray eclipse, it could not be caused by reprocessed X-rays. These Hα pulsations could not be confirmed in observations by Nelson et al. (1979) or Thomas et al. (1981), however.

Reprocessed UV pulses were reported from 4U0900-40 by Boroson et al. (1996a), who found a pulsed fraction of ~ 0.03 in the Si IV doublet near 1402 Å and in the N V line near 1241 Å. The orbital phase of the system was $\phi \sim 0.46$ during the observations, where X-ray eclipse (superior conjunction of the X-ray source) is centered at $\phi = 0$. The UV pulse period was reported by Boroson et al. (1996a) to be the same as that of the X-ray pulses observed simultaneously, 283.33 s. Boroson et al. found the UV pulses occurred in N V and Si IV recombination lines. They speculated that the pulses originated in the stellar wind outflow from the B0.5Ib primary. Boroson et al. (1996b) also report reprocessed UV pulsations from Her X-1 in the N V line at orbital phases 0.6–0.9. These authors inferred that the UV pulses were reprocessed both in the accretion disk surrounding the NS and in the X-ray heated atmosphere of the companion star, HZ Her.

We observed 4U0900-40 and the X-ray transients A0535+26, A1118-61, and 4U1145-619 in the UV to search for reprocessed X-ray pulses. Each of these systems has been observed to contain an X-ray pulsar. The structure of the companion star's atmosphere at the depth at which the X-rays are absorbed (a few g cm^{-2}) would be consistent with the re-radiation of this energy preferentially in recombination lines from multiply ionized species. Their ionization state would be affected by the temperature variation caused by the variable energy input from the X-ray pulses. For OB stars, these emission lines fall primarily in the far UV. We chose a 200 Å wide bandpass in the UV that includes the resonance lines of Si IV (1394 and 1403 Å), ionization potential (IP) 45 eV; C IV (1551 Å), IP 64 eV; and O V (1371 Å), IP 113 eV. C II (1335 Å), IP 24 eV, is at the edge of the bandpass. We confirm the emission of reprocessed UV pulses from HD77581 (= 4U0900-40). We report upper limits to the modulation of the UV flux from A1118-61 eleven months after an X-ray outburst, and from A0535+26 and 4U1145-619 in quiescence. We also give upper limits to the flux in our UV bandpass from the systems 1E1145.1-6141, GX304-1, and 4U1538-52.

2. Observations

All observations were obtained with the High Speed Photometer (HSP), one of the first-generation instruments on board the Hubble Space Telescope (HST). A description of the HSP and its method of operation is given by Bless et al. (1997). Photometric observations were obtained using the F145M filter, which defined a 200 Å wide bandpass (FWHM response to a flat incident spectrum) centered at 1450 Å (Bless et al. 1992). All observations used a 1.0″ circular aperture. Flux densities were calibrated by observations of BD +75° 325, an O5p IUE spectrophotometric standard.

The X-ray binaries observed are listed in Table 1, together with the starting time and duration of each continuous observation. The X-ray pulse period in each system is > 100 s; each observation used a sample time of 1.0 s. The uncertainty of the mean counting rate is derived from the variance of the counting rate about its mean, and does not include the systematic uncertainty in HSP photometry caused by the spherical aberration of the HST mirror in conjunction with milliarcsecond variations in target centering (Dolan et al. 1994). The orbital ephemerides from which the binary phases at the epochs of observation were calculated are given in Sect. 3 for each individual source. For transient sources, the binary phase is normalized to X-ray outburst at $\phi = 0$; for 4U0900-40, the orbital phase is referred to superior conjunction of the X-ray source at $\phi = 0$.

3. Results

3.1. 4U0900-40

4U0900-40/HD77581 is an eclipsing binary system with a B0.5Ib primary and a NS secondary. We adopt for it the ephemeris of Sato et al. (1986), where the time of superior conjunction of the X-ray source is T_0 = JD 2 445 785.28 $\pm$ 0.08, and the orbital period is 8.96426 $\pm$ 0.00018 d. The X-ray eclipse extends from $\phi \sim 0.92$ to $\phi \sim 0.08$ (Dolan et al. 1981). The NS is an X-ray pulsar. Lutovinov et al. (1994) measured its rotational period to be 283.326 $\pm$ 0.020 s on 1992 June 13, six months before our observations. The X-ray pulse profile is essentially unchanging over a timescale of years; Fig. 21 of Lutovinov et al. shows a typical shape. The double-peaked structure occurring over one pulse period suggests that we are observing radiation from both magnetic poles of the NS. Boynton et al. (1986) and Deeter et al. (1987) found the NS orbit to be slightly elliptical, $e = 0.089 \pm 0.003$, and give $(a_x/c)\sin i = 112.7 \pm 0.5$ s based on X-ray pulse timing.

We observed HD77581 on 1993 January 6. The observation started at an orbital phase near the onset of X-ray eclipse, $\phi = 0.921 \pm 0.011$, where the uncertainty in the phase is propagated from the uncertainty in T_0 and period given by Sato et al (1986). An occultation of the X-ray source during the 48 minute observation would make any reprocessed X-ray pulses disappear at the same time. Hence, we searched for reprocessed UV pulses of the type reported by Boroson et al. (1996a) by using the Gabor transform (Boyd et al. 1995), a type of short-time-windowed Fourier transform. The Gabor transform of our data set is shown in Fig. 1. We detected UV pulses at the second and third harmonics of the X-ray pulse frequency during the first 600 s of our observation. The power at these frequencies then decreased rapidly to the level associated with the random variations about the mean of the data set. Power from reprocessed X-rays is largest at harmonics of the 283 s X-ray pulse period because the pulse profile consists of two different intensity pulses per NS rotation period, requiring the higher harmonic Fourier components to represent it. The temporal behavior of the power at these frequencies is consistent with the disappearance of the UV pulsation being caused by the occultation of the X-ray pulsar.

The exact period of the modulation is not well determined by an auto-correlation function analysis (ACF) because its time-resolution is only 1 s, nor by a power-spectrum function analysis (PSF), because the frequency resolution of the PSF in the 600 s data set is only 1.67 mHz and the rotational frequency of the NS is 3.53 mHz. We therefore searched the first 600 s of our data for the most likely period of the pulses using the Rayleigh test (Mardia 1972), which does not depend on the unknown phase of maximum of the variation. We investigated periods in the range 282.8 s $\leq p \leq$ 283.8 s, corresponding to maximum velocity differences of $\pm$ 500 km s^{-1} from the X-ray pulse period. These velocities are more than twice as large as any orbital or rotational velocity known to exist in the system. We summed the power in the periods of the fundamental and first 2 harmonics (i.e., at p, p/2, and p/3) (DeJager et al. 1988). We found a maximum in the Rayleigh test statistic at the 99.95% level of significance (= 3.5σ) for p = 283.30 $\pm$ 0.10 s at the spacecraft. We emphasize that this uncertainty is formal only; the width of the harmonics in Fig. 1 in frequency space corresponds to a width larger than 0.10 s in period space. The maximum in the Rayleigh test statistic is broad in period space because only 2 cycles of the modulation are present in 600 s of data. One slightly larger maximum in the Rayleigh statistic occurs in the range 280 s $< p <$ 286 s, at 283.82 $\pm$ 0.06 s at the spacecraft. When corrected to the heliocenter, this would correspond to a velocity of $\pm$ 540 km s^{-1} relative to the center of mass of the binary. We consider this period to be an alias of the 283.30 s period.

The data folded modulo the 283.30 s period are shown in Fig. 2 with pulse phase 0.95 arbitrarily corresponding to the start of our observation. The UV pulse profile closely resembles both the typical pulse profile seen in X-rays at energies above 6 keV (Lutovinov et al. 1994; Staubert et al. 1980) and the UV pulse profile detected near ϕ = 0.46 by Boroson et al (1996a). All profiles consist of two peaks separated by $\sim$ 0.5 in phase. One maximum has a higher intensity than the other; the minimum following the higher intensity peak is not as low as the other interpeak minimum. The lower peak also appears to have a longer rise to maximum in both X-ray and UV pulse profiles. Published X-ray pulse ephemerides do not allow us to establish the X-ray pulse phase of our observations and so we can not compare the relative alignment of the X-ray and UV peaks. Correcting the period of the UV pulses we detect from 4U0900-40 for the orbital velocity of the spacecraft and the Earth during our 600 s observation gives a heliocentric period of 283.32 $\pm$ 0.10 s.

If we define the pulsed fraction as

$$\mathrm{PF} = (\bar{S} - S_0)/\bar{S}, \qquad (1)$$

where $\bar{S}$ is the mean counting rate per bin in Fig. 2 (713.2 $\pm$ 1.8 s^{-1}) and S_0 is the minimum counting rate in any bin (704.8 $\pm$ 3.5 s), then PF = 1.2 $\pm$ 0.6%.

3.2. A1118-61

A1118-61 is a recurrent X-ray transient, first observed in outburst on 1975 December 20. The X-ray flux was pulsed with a period of 405.3 $\pm$ 0.6 s (Ives et al. 1975). The flux decayed to background over the following two weeks. The optical counterpart of the system is the Be star He3-640 = Wray 793, of spectral type O9.5 IV-Ve (Janot-Pacheco et al. 1981; Coe & Payne 1985). X-ray transients in a Be star system with pulse periods $>$ 100 s are probably caused by accretion onto a rotating NS secondary. The accretion occurs when the NS passes through the Be star's dense wind (or extended atmosphere) near periastron (Motch et al. 1988). The only other detected outburst of A1118-61 started 1992 January 1 (Brandt et al. 1993). This outburst was larger than the first; the X-ray source was still detectable on 1992 March 9 (Coe et al. 1994). The X-ray pulse period was originally 406.57 $\pm$ 0.05 s but gradually decreased to 406.34 $\pm$ 0.02 s over a month and then fluctuated around that period (Coe et al. 1994). The X-ray pulse profile consisted of a

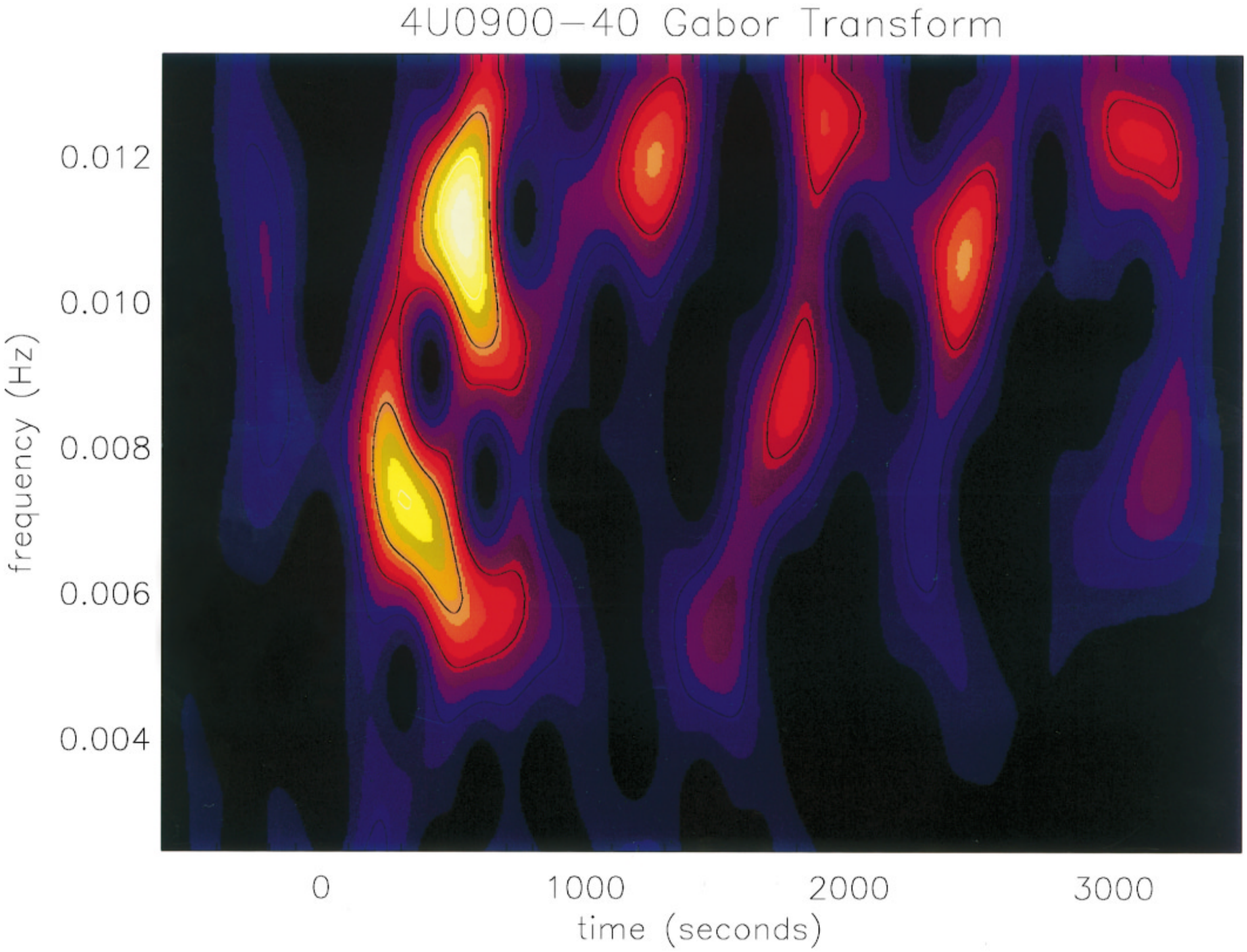

Fig. 1. The Gabor transform of the 4U0900-40 counting rate in the F145M bandpass using a 600 s wide time-window. Contours of equal power are shown; power increases from black (lowest power) through red to yellow and white. The observation was 2,880 s long; the data was padded to 4,096 s with random numbers (gaussian white noise) having the same mean and variance as the data. The time evolution of the frequencies between 2 mHz ($p = 500$ s) and 14 mHz ($p = 71$ s) is shown. The strong signal in the first 600 s of data peaks at the 2nd and 3rd harmonics of the 283 s (3.5 mHz) X-ray period because the pulse profile consists of two different intensity peaks per NS rotation period.

single peak with FWHM 0.37 in phase. The pulsed fraction in X-rays is very large, $\sim 85\%$ (Ives et al. 1975).

We observed He3-640 (= A1118-61) on 1992 December 29, almost one year after the onset of the second X-ray outburst. If the two outbursts correspond to successive periastrons of the NS (unlikely though that possiblity may be), then the period of the system is 17.0 years and our observations occurred at $\phi \sim 0.05$ after periastron. (Note that this hypothetical phase is not referred to the superior conjunction of the X-ray source.) We searched the 2,880 s long data set for a periodic signal using both the ACF and PSF techniques (Percival et al. 1995). The ACF is most sensitive to a step-function pulse profile; the PSF, to a purely sinusoidal one. Real pulse profiles are usually somewhere between these two extremes in shape. A peak appeared in the ACF at the 2.9σ level of significance at a lag time of 409 s; the ACF at half this lag (205 s) was significantly above the mean ACF, at the 2.4σ level of significance. Neither peak can be considered as a significant detection under the usual assumptions of time-series analysis. The PSF showed excess power at a period of 206 s (14 cycles in 2,880 s), but only at a level that is exceeded by $\sim 40\%$ of all random distributions with no signal in them having the same mean and variance as our data set.

The Rayleigh test showed a maximum at the 2.5σ level of significance when the data were folded modulo 204.51 s at the spacecraft. If this were a signal from A1118-61, its heliocentric period would be 204.52 s. This is $\sim 1/2$ the period of the X-ray pulsar. It might be argued that the X-ray period is the true rotational period, and that we see two UV pulses per NS rotation because the Be star intercepts the X-ray beam from both NS magnetic poles while the Earth intercepts only one. Although the pulse profile of our data folded modulo 204.5 s shows a sinusoidal shape, that folded modulo 409.0 s shows no clear pattern.

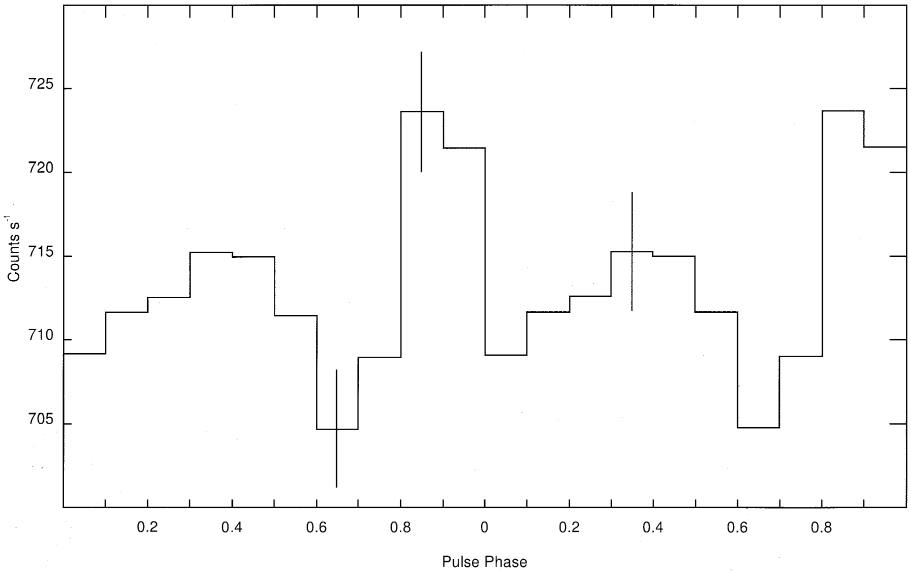

Fig. 2. The counting rate of 4U0900-40 in the F145M bandpass during the first 600 s of our observations, folded modulo the 283.30 s period at the spacecraft found using the Rayleigh statistic. The data are repeated twice for clarity. The $\pm 1\sigma$ uncertainty on the counting rates is shown for three typical phase bins. The starting time of our observations was arbitrarily assigned pulse phase 0.95. The data were pre-whitened to remove a long-term trend in the counting rate caused by heating effects on the secondary truss of HST. The UV pulse profile closely resembles the pulse profile seen in X-rays.

Both "pulse profiles" are consistent with a random distribution about the mean under the assumptions of the χ^2 test.

We interpret our results as indicating that $< 4.0\%$ of the flux from A1118-61 in the F145M bandpass is pulsed with a period near that of the X-ray pulses during our observation. We derived this upper limit by adding an artificial signal with p' = 300 s to our data set. The signal's mean count rate was 0.124 s^{-1}, or 4% of the mean count rate from A1118-61. The input pulse shape was of form $\sin^2 \phi_i$, where ϕ_i represents the phase of the ith 1-second bin within the 300 s period of the artificial signal. The single pulse was 150 s wide at zero maximum; no counts were added from ϕ_i = 0.5 to 1.0. (The FWHM of the $\sin^2 \phi_i$ curve is 0.25 in ϕ_i.) The probability P_i of bin i receiving a count was

$$P_i = N \sin^2 \phi_i / \sum_{i=1}^{150} \sin^2 \phi_i, \qquad (2)$$

where N is the total number of counts per 300 s period in the pulse. No attempt was made to replicate Poisson statistics with regard to bins containing more than one count. For A1118-61, N = 300 s (0.124 s^{-1}) = 37. p' = 300 s was chosen for A1118-61 to be similar to the X-ray pulse period, but not near it. We detected this signal at the 3.0σ level of significance in the PSF at a frequency of 10 cycles per 2,880 s, and at the 1.6σ level of significance at the frequency of the first harmonic, 19 cycles per 2,880 s. Assuming a 3σ level of detection to be significant gives the upper limit we quote.

3.3. A0535+26

A0535+26 is a repetitive X-ray transient whose X-ray flux is pulsed with $p \sim 104$ s (Rosenberg et al. 1975). Its optical counterpart is HDE245770, a B0Ve star (Wade & Oke 1977). Priedhorsky and Terrell (1983) find a periodicity of 111.0 $\pm$ 0.4 d between outbursts, presumably the orbital period of a NS about the primary. We observed HDE245770 on 1993 January 5. An X-ray outburst was observed from the source on 1993 July 8 (JD 2 449 177), and lasted for longer than one week (Wilson et al. 1993); its pulse period in 20–120 keV X-rays was 103.377 $\pm$ 0.005 s.

Using JD 2 449 177 as the time of onset of an outburst, we observed A0535+26 at ϕ = 0.34 $\pm$ 0.01, where the phase is referenced to the onset of X-ray outburst. (Using the original T_0 of Priedhorsky and Terrell (1983) gives ϕ = 0.45 $\pm$ 0.24.) No significant feature was found in the ACF or PSF of our data near the pulse period of A0535+26 (or near its harmonics). We interpret this to mean that $< 0.7\%$ (detection at the 3σ level of significance) of the flux in the F145M bandpass from HDE245770 was pulsed with any period near 104 s during our observation. We derived this upper limit using the same technique of adding an artificial signal to our data set described above.

3.4. 4U1145-619

4U1145-619 is a repetitive X-ray transient whose X-ray flux is pulsed with $p \sim 292$ s (Cook & Warwick 1987). Its optical counterpart is HD102567, a B1Ve star (Bianchi & Bernacca 1980). The X-ray source undergoes outbursts every 186.5 d (Cook & Warwick 1987), which is the orbital period ascribed to a NS secondary. Outbursts typically last 10 d. We observed HD102567 on 1993 August 8. An X-ray outburst was observed from the source with onset 1994 March 12.5 (JD 2 449 424.0); its barycentric pulse period during this outburst was 293.4464 $\pm$ 0.0016 s in 20–40 keV X-rays (Wilson et al. 1994).

Using JD 2 449 424.0 as T_0, we observed 4U1145-619 at ϕ = 0.84, where the phase is referenced to the onset of X-ray outburst. (The jitter in the phase of outburst given by Cook and Warwick (1987) is typically $\pm$ 0.03.) No significant feature was found in the ACF or PSF of our data near the pulse period of 4U1145-619 (or near its harmonics). We interpret this to mean that $< 0.2\%$ (3σ upper limit) of the flux in the F145M bandpass from HD102567 was pulsed with any period near 293 s during our observation.

Table 2. Flux Density in the F145M Bandpass

Star	X-ray Pulsar	m_V	Spectral Type	E(B-V)	Flux Density (mJy)
HD245770	A0535+26	9.1	B0Ve	0.8[a]	53 ± 1
HD77581	4U0900-40	6.7	B0.5Ib	0.76[b]	261 ± 6
He3-640	A1118-61	12.1	O9.5IV-Ve	0.9[c]	1.15 ± 0.03
HD102567	4U1145-619	9.2	B1Ve	0.45[d]	387 ± 8
-	1E1145.1-6141	13.1	B2Iae	2.0:[e]	< 0.003
-	GX304-1	14.7	B2Vne	1.7[f]	< 0.003
QV Nor	4U1538-52	14.4	B0Ie	2.4[g]	< 0.004

[a] Wade & Oke 1985.
[b] Hyland & Mould 1973.
[c] Coe & Payne 1985.
[d] Hammerschlag-Hensberge et al. 1980.
[e] Hutchings, Crampton, & Cowley 1981.
[f] Parkes, Murdin & Mason 1980.
[g] Parkes, Murdin & Mason 1978.

3.5. Other sources

We also observed the optical counterparts of the X-ray pulsars GX304-1 (= 4U1258-61) on 1993 June 3, starting JD 2 449 142.484; 1E1145.1-6141 on 1993 October 5, starting JD 2 449 265.934; and 4U1538-52 on 1993 September 21, starting JD 2 449 251.543. No flux above background was detected from any of these systems in the F145M bandpass. The corresponding 3σ upper limit on the flux density from these stars at the epoch of our observation is given in Table 2, together with the flux densities observed from the four detected stars.

4. Discussion

4.1. The UV pulses from 4U0900-40

4.1.1. Spectrum

Davidsen et al. (1975) attributed the optical pulses they detected from HZ Her at the 1.24 s X-ray pulse period to pulsed emission in lines such as He II λ4686 and N III λ4640. The amplitudes of pulsation in these lines would have had to exceed 25% to reproduce the pulsed fraction they observed in their bandpass. In theory (Chester 1979), most of the X-ray energy is absorbed at the top of the primary's atmosphere (i.e., at small continuum optical depth) by photoelectric absorption. Radiative recombination to the original ionization state of the absorbing atom will then produce line emission on a time scale $\ll 1$ s (Davidsen et al. 1975; Chester 1978). Chester (1979), however, calculated the pulsed fraction around 4000 Å only in the continuum because Nelson et al. (1977) reported that the pulses from HZ Her have the same spectrum as the unpulsed spectrum and arise primarily from heating of the stellar surface, not from emission lines.

The mechanism generating pulses in the far UV in 4U0900-40 is different from that generating continuum pulses in the visible in Her X-1, however. Several strong resonance lines of abundant metals occur in the F145M bandpass, and these emission lines can act as efficient radiators of any temporary input of excess energy. We examined 49 archival IUE spectra of HD77581, reduced using NEWSIPS, which included the 1350–1550 Å region of its spectrum. The spectra were taken at many different phases and epochs (cf. van Kerkwijk et al. 1995b). Eight were taken at different phases during two consecutive orbits (Sadakane et al. 1985). Strong resonance lines of Si IV (1394 and 1403 Å), C IV (1551 Å), O V (1371 Å) and C II (1335 Å) lie within (or in the wings of) the F145M bandpass. The ionization potential (IP) of these ions ranges from 24 to 113 eV. The lines have P Cygni profiles, indicating that a major part of the emission arises in the wind associated with the primary.

The absorption trough on the blue wing of the Si IV λ1403 line exhibits an emission feature, the equivalent width of which varies with orbital phase. After removing five overexposed spectra, and applying a 7-point rectangular smoothing function, we measured the equivalent width of the feature in 30 spectra relative to the equivalent width of the same feature in spectrum SWP22301, which was obtained during X-ray eclipse (at ϕ = 0.04). We applied a linear interpolation across any saturated pixels and reseau marks in each spectrum, and corrected for a linear degradation in SWP camera sensitivity of 1% per year. The ratios we found vary by nearly a factor of 2 over the orbit (Fig. 3). The integrated flux in the feature is strongly correlated with orbital phase, reaching its maximum value when the entire visible hemisphere of the primary is illuminated by the X-ray source (at $\phi = 0.5$) and its minimum value during X-ray eclipse. This variable emission in the absorption trough of the Si IV line was not found previously by other observers who analyzed the same spectra (e.g., Sadakane et al. 1985) because the Si IV line is dominated by fluctuations in the emission from the outflowing wind structure, and previous observers measured the integrated flux of the entire line. It is also necessary to renormalize the zero point of each spectrum's flux scale from that given in the IUE archive by adding the same constant flux level, 7 x 10^{-13} erg cm^{-2} s^{-1} $Å^{-1}$, to each spectrum so that no negative fluxes occur in any spectrum. This renormalization corrects the spectrum for an incorrectly subtracted global background, which is measured in the standard IUE reduction procedure between the echelle or-

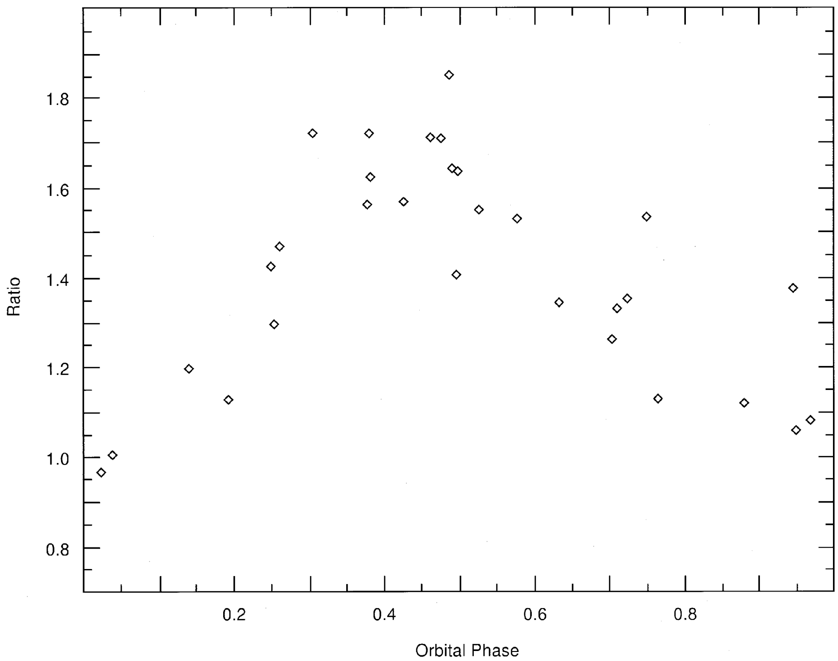

Fig. 3. The ratio of the integrated flux at the center of the Si IV λ1402.77 line P Cyg absorption profile between 1395 Å and 1405 Å, relative to the flux during X-ray eclipse. The dispersion in values of the ratio at a single phase is representative of the uncertainty on a single measurement.

ders. The feature we measured occurs only in the center of the absorption trough, is a small fraction of the total flux in the line, and is revealed clearly only by taking the ratio of the fluxes in spectra at two different phases. The ratio we measured is unity at wavelengths in the absorption line away from the emission feature for all of the spectra we compared. The same type of emission feature occurs outside of eclipse in the λ1394 line of the Si IV doublet and in the other strong resonance lines in the F145M bandpass. IUE spectra are too noisy in this wavelength region to gain any additional information about this effect from its phase dependence in the other absorption lines.

The area of the visible hemisphere of a spherical star illuminated by an X-ray source at large distance from the star in a circular orbit with i = 90° is

$$A = (A_0/2)[1 - \cos(2\pi\phi)], \quad (3)$$

where A_0 is the area of the visible hemisphere (= $\pi R_\star^2$). A is 0 at ϕ = 0, and has a maximum at ϕ = 0.5. The illuminated area has the same sinusoidal dependence on phase as the integrated flux ratio of the Si IV feature we observed. The energy being radiated in the Si IV feature has an integrated flux that is directly proportional to the area of the visible hemisphere being illuminated by X-ray pulses. This is consistent with Boroson et al.'s (1996a, 1996b) finding that the reprocessed UV pulses occur in the resonance lines of metals. The wide range of IP's among the species having resonance lines in the F145M bandpass, and the effectiveness of resonance line radiation from metals in cooling a heated gas, implies that reprocessed UV line radiation in this bandpass should be prominent at every phase at which the X-ray pulsar illuminates a significant part of the primary's visible hemisphere.

4.1.2. Location of the emission region

The heliocentric period of the UV pulses we observed is 283.32 $\pm$ 0.10 s. The heliocentric X-ray pulse period 6 months before our observation was 283.326 $\pm$ 0.020 s (Lutovinov et al. 1994). Neglecting for purposes of this discussion the non-circulararity of the orbit of the NS (e = 0.089 [Deeter et al. 1987]), the primary sees the synodic pulse period of the X-ray pulsar rather than its siderial period (Middleditch et al. 1981), $p_s = pp_o/(p_o \pm p)$, where p is the siderial rotation period of the NS, p_o is the orbital period, and p_s is the synodic period observed at the primary. The negative sign holds if the orbital and rotational angular momenta of the NS are parallel (i.e., for direct rotation of the NS), and the positive sign if they are anti-parallel (retrograde rotation). The period of the UV pulses we observed at ϕ = 0.92 is shifted from p_s by -0.11 $\pm$ 0.10 s for direct rotation, and by +0.10 $\pm$ 0.10 s for retrograde. A period shift of 0.10 $\pm$ 0.10 s would be caused by the Doppler shift corresponding to a radial velocity of 105 $\pm$ 105 km s^{-1}. Both the orbital velocity of the primary, $\sim$ 20 km s^{-1} (van Kerkwijk et al. 1995b) and its rotational velocity, $v \sin i \sim$ 130 km s^{-1} (Dolan et al. 1981), lie within this velocity range. The outflow velocity of the stellar wind is $\sim$ 500 km s^{-1} at the distance of the NS (Kaper, Hammerschlag- Hensberge, & Zuiderwijk 1994; Boroson et al. 1996a), so the UV pulses are unlikely to originate in a region co-moving with the stellar wind.

Boroson et al. (1996a) also note that the pulsation they see in the λ1403 Si IV line near ϕ = 0.46 has a central wavelength near the rest wavelength of the line, and is not blue-shifted by the amount expected if it arose in the stellar wind. The spectrum of the UV pulses detected by Boroson et al. (1996b) from HZ Her had both a broad and a narrow component in wavelength space. These authors attributed the narrow component, with FWHM similar to that of the emission feature we detect in IUE spectra, to reprocessed X-rays from the atmosphere of HZ Her. The only consistent interpretation for all of these observations requires the UV pulses we observe from 4U0900-40 to arise in the atmosphere of the supergiant. The optical depth of the stellar wind in these resonance lines must be small enough to allow a significant pulsed flux to emerge from the system.

4.2. X-Ray transients

No UV signal with a period near that of the X-ray pulses was found in our observations of the X-ray transients A1118-61, A0535+26, and 4U1145-619. Because these systems are usually modeled as a NS + Be star binary with an elliptical orbit, their X-ray outbursts should occur near periastron. The lack of UV pulses from the optical star is then naturally explained by the low X-ray luminosity at the orbital phases at which we observed (Table 1). The one exception may be A1118-61, which was observed at $\phi = 0.05$ if one assumes the 17 years between its two known X-ray outbursts is an orbital period. Its X-ray luminosity may have been non-zero when we observed it 12 months after the onset of its nearest previous outburst (cf. Coe et al. 1994). It is only speculation, however, to link the non-significant UV signal we detected in A1118-61 with this possibility.

Because reprocessed X-ray pulses are not seen over most orbital phases in these binaries, X-ray transients are poor candidates for systems in which to determine the mass of the NS by using the double-lined spectroscopic binary technique. The binary companions of non-transient X-ray pulsars are more likely to exhibit UV pulses at most orbital phases (those at which the X-ray pulses are visible at Earth) and should be more suitable candidates for investigations attempting to determine the mass range of NS. (A list of X-ray pulsar systems is given by Nagase (1989), but note the misprint in the HD number of the optical counterpart of 4U1145-619 in his Table 1.)

5. Conclusions

We confirm the detection of reprocessed X-ray pulses from the 4U0900-40 system in the far UV reported by Boroson et al. (1996a). The 1350–1550 Å bandpass we used includes resonance lines of several different metals having a wide range of ionization potentials. We find evidence in archival IUE spectra that the energy absorbed from the X-ray pulses is re-radiated primarily in the resonance emission lines of metals, consistent with the results of Boroson et al. (1996a). The UV pulses appear to originate in the outer atmosphere of the supergiant primary. These pulses should be visible at all orbital phases outside of X-ray eclipse. The determination of NS masses in X-ray binary systems using the Doppler shift of reprocessed pulses in the UV appears to be feasible if the pulses arise in the atmosphere of the primary.

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