

Letter to the Editor

The complex X-ray spectrum of the low-mass X-ray binary 4U 1626–67

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Abstract. We report on observations of the X-ray pulsar 4U 1626–67 by the LECS instrument on-board *BeppoSAX*. We confirm the recent ASCA discovery of excess emission near 1 keV (Angelini et al. 1995). The pulse period of 7.66794 ± 0.00004 s indicates that the source continues to spin-down. The phase averaged spectrum is well fit by an absorbed power-law of photon index 0.61 ± 0.02 and a blackbody of temperature 0.33 ± 0.02 keV, together with an emission feature at 1.05 ± 0.02 keV. This spectral shape is similar to that observed by ASCA during the spin-down phase, but significantly different from measurements during spin-up. This suggests that the change in spectrum observed by ASCA may be a stable feature during spin-down intervals. The source intensity is a factor ~ 2 lower than observed by ASCA three years earlier, confirming that 4U 1626–67 continues to become fainter with time.

Key words: stars: – individual: (4U 1626–67) – stars: neutron – X-rays: stars – stars: binaries: close

1. Introduction

The X-ray source 4U 1626–67 is a 7.7 s pulsar in a highly compact binary system of orbital period 2485 s. It is unusual in that it is one of the few low mass X-ray binary systems to contain an X-ray pulsar. While the X-ray emission is strongly modulated by the pulsar, there is no evidence for Doppler shifts induced by the orbital motion of the source, despite extensive searches. This implies that the projected orbital radius of the neutron star is small, i.e., $a_x \sin i \leq 13$ m-lt-s (Levine et al. 1988). Optical pulsations were first detected by Ilovaisky et al. (1978) and interpreted as X-ray re-processing near to, or along, the line of sight to the X-ray source. Middleditch et al. (1981) found a single low frequency side-lobe which they interpret as arising from the optical re-processing of the primary X-rays on

the companion star. Assuming the pulsar spins in the same sense as the orbital motion, these photons will be shifted to a lower frequency by the rotation frequency of the binary orbit. From the observed frequency shift of 0.4 mHz an orbital period of 2485 s and a projected semimajor axis of 0.4 lt-s is inferred. The current picture of 4U 1626–67 is of a highly compact system comprising a neutron star of mass $\sim 1 M_\odot$, with a $0.08 M_\odot$ Main Sequence or $0.02 M_\odot$ white dwarf companion (Verbunt et al. 1990).

For the first decade after its discovery 4U 1626–67 was rapidly spinning-up at a rate of $\dot{P}/P \sim -2 \times 10^{-4} \text{ yr}^{-1}$. However, long term monitoring by the Burst and Transient Source Experiment (BATSE) on-board the Compton Gamma-ray Observatory beginning in 1991 April found that \dot{P} , and hence the accretion torque, had changed sign, resulting in a spin-down at nearly the same rate (Wilson et al. 1993). It is estimated that the reversal occurred in mid-1990. Observations of 4U 1626–67 during the earlier spin-up phase found that the phase averaged spectrum could be modeled by a blackbody of temperature, kT, ~ 0.6 keV together with a power-law of photon index, α , of ~ 1 (e.g., Pravdo et al. 1979; Kii et al. 1986). In the 2–10 keV energy range the pulse profile consisted of a narrow pulse with a “notch”, while at higher and lower energies this evolved into a roughly sinusoidal shape (Levine et al. 1988; Mavromatakis 1994). This strong energy dependence may result from anisotropic radiative transfer in a strongly magnetized plasma (Kii et al. 1986).

In addition to periodic pulsations, 4U 1626–67 also exhibits quasi periodic behavior. Both the X-ray and optical intensities show correlated flaring on timescales of ~ 1000 s (Joss et al. 1978). The origin of this behavior is unknown. A 40 mHz quasi periodic oscillation (QPO) has been detected in X-rays (Shinoda et al. 1990) and more recently in the optical band (Chakrabarty et al. 1997).

Finally, the recent observation of an emission line complex near 1.0 keV by Angelini et al. (1995) is particularly interesting. This emission is interpreted as arising primarily from Ne K

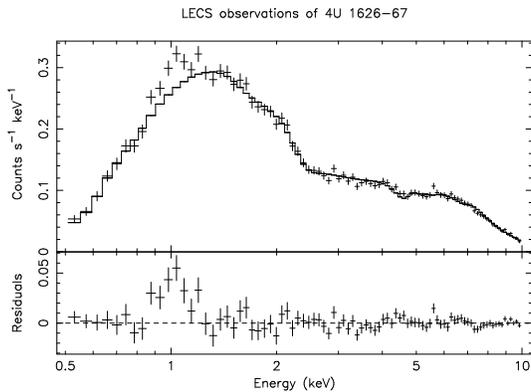


Fig. 1. Phase averaged data and folded model for 4U 1626–67. The data are described by a model consisting of a blackbody of $kT = 0.33$ keV, a power-law of $\alpha = 0.61$, an emission-line centered on 1.05 keV and low energy absorption. For illustrative purposes, the line intensity is set to zero. The lower panel shows the residuals

rather than from Fe L, based on the measured line energies and intensities. This result suggests that the companion star has evolved past its hydrogen burning stage. Ne is a by-product of He burning and therefore its overabundance suggests that the star is burning, or has burnt, He.

2. Observations

The Low-Energy Concentrator Spectrometer (LECS) is one of 5 scientific instruments on-board the *BeppoSAX* satellite (Boella et al. 1997). The LECS is described in Parmar et al. (1997) and consists of a nest of conical approximation to Wolter I X-ray mirrors which produce a focused beam of X-rays on an imaging gas scintillation proportional counter. The detector employs a driftless design which, in conjunction with an extremely thin entrance window, ensures an extended low energy response. The nominal energy range of the instrument is 0.1–10 keV and the full width at half maximum (fwhm) energy resolution is 19% at 1 keV. The field of view (fov) is $37'$ diameter and the spatial resolution is $5.1'$ fwhm at 1 keV. *BeppoSAX* was launched into a 600 km equatorial orbit on 1996 April 30.

4U 1626–67 was observed twice by the LECS during the Science Verification Phase on 1996 August 6 from 12:00 UT to 21:50 UT and on August 9 02:25 UT to August 11 00:00 UT. The total source exposure is 40 ks and the mean LECS count rate is 1.029 ± 0.005 s $^{-1}$. Because of the large spatial extent of the point spread function, background data were acquired separately by viewing blank regions of sky. Background subtraction is not critical for such a bright source.

3. Spectral analysis

Source events were obtained from both observations using the standard extraction radius of $8'$, centered on the source centroid. The extracted data were rebinned to have bin widths of $0.25 \times$ the fwhm energy resolution. This is to help ensure an unbiased

fit across the energy range, while preserving sensitivity to line features. Since the LECS response is dependent on both position within the fov and extraction radius, the appropriate matrix was created using SAXLEDAS version 1.4.0 (Lammers 1997).

The spectrum was first fit with an absorbed blackbody plus power-law model yielding a χ^2 of 115 for 84 degrees of freedom (dof). Inspection of the residuals (see Fig. 1) shows an excess centered around 1 keV, similar to that seen by Angelini et al. (1995) with the ASCA solid-state imaging spectrometer (SIS). The addition of a Gaussian line feature to the model results in a χ^2 of 92 for 81 dof. An F-test shows that the improvement is significant at the $\geq 99.99\%$ level. The best-fit line energy and flux are 1.05 ± 0.01 keV and $(4.58 \pm 1.5) \times 10^{-4}$ photons cm $^{-2}$ s $^{-1}$, respectively. (All uncertainties are quoted at 68% confidence.) The equivalent width (EW) is 47.6 ± 13.5 eV. The spectrum is shown in Fig. 1 with the line intensity set to zero. The best-fit values of kT and α are 0.33 ± 0.02 keV and 0.61 ± 0.02 , respectively. The derived absorption column is $(6.9 \pm 2.0) \times 10^{20}$ atoms cm $^{-2}$, consistent with the interstellar value in the direction of 4U 1626–67 (Daltabuit & Meyer 1972; Dickey & Lockman 1990).

The best-fit line energy agrees well with that expected from a blend of 80% Ne Ly- α (1.021 keV) and 20% Ne He- β (1.084 keV) emission, consistent with the ASCA result of Angelini et al. (1995). The values of kT and α are also similar to those measured using ASCA, but both a factor of 2 lower than earlier HEAO-1 (Pravdo et al. 1979) and *Tenma* (Kii et al. 1986) values. The blackbody radius, r_b , of 1.0 d $_{kpc}$ km, where d $_{kpc}$ is the distance in kpc, is also consistent with ASCA. The 0.5–10 keV luminosity is 2.0×10^{34} ergs s $^{-1}$ d $_{kpc}^2$ which is $\sim 40\%$ lower than measured by ASCA three years earlier, and a factor of 6 lower than that derived using the *Einstein* Solid State Spectrometer in 1979 March (Angelini et al. 1994). In the case of ASCA, Angelini et al. (1995) attribute the spectral and luminosity differences to the torque reversal, since the HEAO-1, *Tenma*, and *Einstein* measurements were carried out prior to mid-1990. The ASCA and *BeppoSAX* measurements were performed during the present spin-down phase.

In order to investigate whether the single narrow feature seen by the LECS is consistent with the emission line complex observed by the ASCA SIS, the feature at 1.05 keV was replaced by the blend of lines used in the ASCA fit (see Table 1 of Angelini et al. 1995). Each line was added separately with its energy and width fixed at the measured ASCA values. The only *proviso* for inclusion in the final fit was that χ^2 must reduce. Only three lines satisfied this criteria; the Ne Ly- α line at 1.021 keV, the Ne He- β line at 1.084 keV, and the O He- α line at 0.568 keV. Surprisingly, the fit did not require an Ne He- α line and we derive an upper flux limit at the 90% confidence level of 2.2×10^{-4} photons cm $^{-2}$ s $^{-1}$. Phase-resolved ASCA spectra reveal the presence of a weak iron K feature over a narrow range of pulse phases (Angelini et al. 1995). Including such a line in the current model gives a χ^2 of 88 for 80 dof. Best-fit spectral parameters are listed in Table 1. The derived O He- α and Ne He- β line intensities are consistent with the ASCA values reported in Angelini et al. (1995). However, the Ne Ly- α line intensity is

Table 1. Best-fit spectral parameters. Uncertainties are given at the 68% confidence level. Line energies, widths and temperatures are in units of keV. Line fluxes and column densities are in units of 10^{-4} photons $\text{cm}^{-2} \text{s}^{-1}$ and 10^{21} atoms cm^{-2} , respectively, EW are given in units of eV, and r_b has units of d_{kpc} km.

Parameter	Value
Model 1: Absorbed power-law plus blackbody	
N_H	1.10 ± 0.20
α	0.64 ± 0.02
kT	0.29 ± 0.01
r_b	1.4 ± 0.8
χ^2/ν	115/84
Model 2: Absorbed power-law, blackbody and line	
N_H	0.69 ± 0.20
α	0.61 ± 0.02
kT	0.33 ± 0.02
r_b	1.0 ± 0.5
E_{line}	$1.05 \pm \begin{smallmatrix} 0.01 \\ 0.03 \end{smallmatrix}$
σ_{line}	0.04 ± 0.04
EW	48 ± 14
Flux $_{line}$	$4.6 \pm \begin{smallmatrix} 1.5 \\ 1.2 \end{smallmatrix}$
χ^2/ν	92/81
Model 3: Absorbed power-law, blackbody and lines	
N_H	0.81 ± 0.26
α	0.62 ± 0.02
kT	0.33 ± 0.02
r_b	1.0 ± 0.6
O He- α 0.568 keV flux	$5.3 \pm \begin{smallmatrix} 8.2 \\ 5.3 \end{smallmatrix}$
EW	34 ± 34
Ne Ly- α 1.021 keV flux	3.2 ± 1.5
EW	28 ± 12
Ne He- β 1.084 keV flux	1.5 ± 1.3
EW	13 ± 10
Fe K- α 6.400 keV flux	0.7 ± 0.5
EW	38.6 ± 22.9
χ^2/ν	88/80

a factor of 3 lower and the 90% confidence upper flux limit to any Ne He- α emission is lower by a factor of ~ 6 .

We next investigated an alternate spectral model for 4U 1626–67 in which the power-law plus blackbody is supplemented by emission from an optically-thin collisionally ionized plasma (specifically the VMEKAL model in XSPEC v.9.01). In principle, this would allow us to estimate the elemental abundances necessary to produce the excess emission around 1 keV, in a similar manner to Angelini et al. (1995). The abundances of Ne and Fe were allowed to vary while the abundances of the other elements were fixed at the photospheric values of Anders & Grevesse (1989). Both high Ne and Fe over-abundances gave acceptable fits to the data with χ^2 's comparable to the ‘‘Ne complex’’ fit. However, the LECS spectrum is of insufficient quality to determine meaningful limits to these abundances.

4. Temporal analysis

The barycentric pulse period during the LECS observations of 7.66794 ± 0.00004 s is in good agreement with the predicted

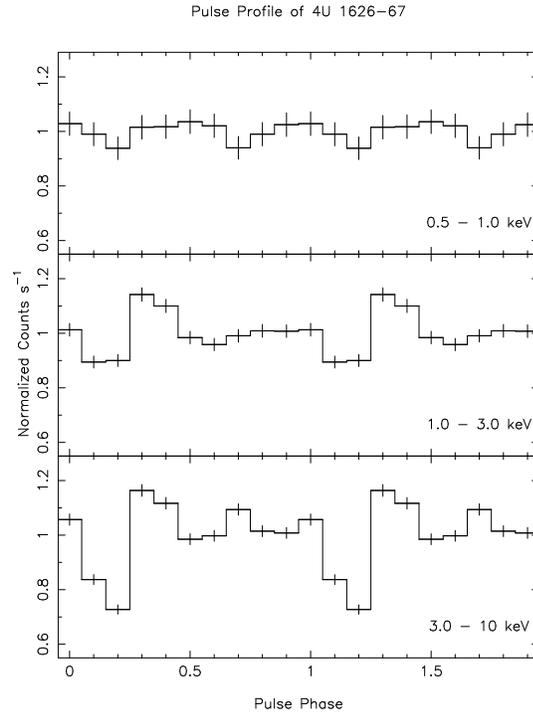


Fig. 2. LECS Pulse profiles for 4U 1626–67 folded over the best-fit period of 7.66794 s in three energy bands

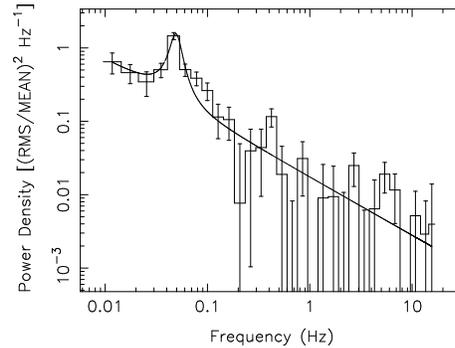


Fig. 3. The power density spectrum for 4U 1626–67 in the 0.1–10 keV energy band. A QPO is visible at ~ 0.05 Hz

value of 7.667943 ± 0.000006 s derived from BATSE data (Chakrabarty 1997). The pulse profiles in the energy ranges 0.5–1, 1.0–3.0, and 3.0–10 keV, are shown in Fig. 2. The overall shape and energy dependence are similar to those seen by ASCA. The pulse profile in the lowest energy band in Fig. 2 may be consistent with that seen during spin-up (e.g., Pravdo et al. 1979), but with a reduced amplitude.

Fig. 3 shows a white noise subtracted, power density spectrum of the LECS data from which quasi periodic oscillations (QPOs) are apparent. The center frequency is 0.049 ± 0.002 Hz and the fwhm is $0.015 \pm \begin{smallmatrix} 0.003 \\ 0.006 \end{smallmatrix}$ Hz. The QPO strength is $18 \pm \begin{smallmatrix} 4\% \\ 9\% \end{smallmatrix}$ rms of the mean count rate. Within uncertainties, the QPO amplitude is the same in the 0.5–2.0 keV and 2.0–10.0 keV energy ranges. The QPO centroid frequency, width, and amplitude are

consistent with the ASCA measurements (Angelini et al. 1995). The amplitude and width are also consistent with the *Ginga* values (Shinoda et al. 1990), but the centroid frequency is not. This change may be related to the torque reversal.

5. Discussion

The LECS data confirm the recent ASCA detection of excess emission near 1 keV from 4U 1626–67. In addition, the best-fit spectral parameters confirm that the spectral shape remains changed following the mid-1990 torque reversal. Both kT and α decreased by a factor of ~ 2 , while the X-ray luminosity decreased by a factor of 6. As before the reversal, the new parameters appear stable with time. Chakrabarty et al. (1997) report that the intensity of the source is steadily decreasing with time. The LECS results support this, since the 0.5–10 keV source intensity is 0.6 that measured by ASCA. Extrapolating from previous measurements (see Fig. 8 of Chakrabarty et al. 1997), the expected decrease is a factor of ~ 0.7 . The shape of the pulse profile is also different from that measured before the reversal. Prior to the reversal, the profile was strongly energy and phase dependent (e.g., see Levine et al. 1988), while the LECS pulse profile has the same shape, but a variable amplitude, over the 1.0–10.0 keV energy range (see Fig. 2).

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