



## *BeppoSAX* observations of the X-ray binary pulsar 4U1626-67

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We report on observations of the low-mass X-ray binary 4U1626-67 performed during the *BeppoSAX* Science Verification Phase. We present the broad-band 0.1-100 keV pulse averaged spectrum, that is well fit by a two-component function: a  $0.27 \pm 0.02$  keV blackbody and an absorbed power law with a photon index of  $0.89 \pm 0.02$ . A very deep and narrow absorption feature at 38 keV, attributable to electron cyclotron resonance, is clearly visible in the broad-band spectrum. It corresponds to a neutron star magnetic field strength of  $3.3 \times 10^{12}$  G. The 4U1626-67 pulse profiles show a dramatic dependence on energy: the transition between the low energy ( $E < 10$  keV) *bi-horned* shape to the high-energy ( $E > 10$  keV) sinusoidal profile is clearly visible in our data. The modulation index shows a monotonic increase with energy.

### 1. INTRODUCTION

The low-mass X-ray binary system 4U1626-67 is formed by a neutron star pulsating at about 7.7 s [1] and orbiting the faint blue star KZ TrA [2]. This system shows the lowest mass function ever observed [3], putting severe constraints on the nature of the optical companion: the most likely is a  $0.02-0.06 M_{\odot}$  degenerate He or CO dwarf [4]. The determination of the 4U1626-67 orbital period have always been problematic: attempts to find Doppler delays in the X-ray pulse arrival times have always been unsuccessful, but photometric studies of the optical companion revealed the presence of two periods: one at the X-ray pulsation frequency [5] and another downshifted by about 0.4 mHz with respect to the first [6]. Assuming that the optical emission is due to the reprocessing of the X-ray emission on the surface of the companion, a binary period of about 2500 s and a projected semi-major axis of 0.4 lt-s are inferred [7].

### 2. OBSERVATIONS

The *BeppoSAX* satellite includes two Wide Field Cameras sensitive in the 2-30 keV range [8], and four Narrow Field Instruments (NFIs) sensitive in 0.1-10 keV (LECS [9]), 1-10 keV (MECS [10]), 3-180 keV (HPGSPC [11]), and 15-300 keV (PDS [12]). It is a program of the Italian Space Agency (ASI), with participation of the Netherlands Agency for Aerospace Programs (NIVR).

During the Science Verification Phase a series of well known X-ray sources were observed in order to check the capabilities and performances of the instruments on-board *BeppoSAX*. 4U1626-67 is one of these sources and it was observed from August 9 00:10:35 to August 11 00:00:05 UTC [13]. Data were telemetered in direct modes, which provide complete information on time, energy and, if available, position for each photon.

### 3. SPECTRAL ANALYSIS

The pulse-phase averaged spectrum of 4U1626-67 has been described in terms of a two compo-

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Table 1  
Best-fit spectral parameters<sup>a</sup>

Parameter		Value		
		No Line	Gaussian	Lorenzian
$N_H$	( $10^{21} \text{ cm}^{-2}$ )	$1.2 \pm 0.2$	$1.1 \pm 0.2$	$1.0 \pm 0.2$
$kT$	(keV)	$0.26 \pm 0.02$	$0.27 \pm 0.02$	$0.28 \pm 0.02$
$r_{bb}$	( $\times d_{kpc} \text{ km}$ )	$1.7^{+0.4}_{-0.2}$	$1.6^{+0.3}_{-0.2}$	$1.5 \pm 0.2$
$\alpha$		$0.90 \pm 0.02$	$0.89 \pm 0.02$	$0.85 \pm 0.02$
$E_c$	(keV)	$21.3^{+0.4}_{-0.3}$	$19.8^{+0.3}_{-0.5}$	$29^{+3}_{-2}$
$E_f$	(keV)	$7.8^{+0.3}_{-0.4}$	$10.5 \pm 0.8$	$9^{+2}_{-1}$
$^b I_{pow}$		$1.11 \pm 0.03$	$1.09 \pm 0.03$	$1.04 \pm 0.04$
$E_{Ne}$	(keV)	$1.05^c$	$1.05^c$	$1.05^c$
$\sigma_{Ne}$	(keV)	$0.04^c$	$0.04^c$	$0.04^a$
$EW_{Ne}$	(keV)	$48^c$	$48^c$	$48^c$
$E_{CRF}$	(keV)		$37 \pm 1$	$33 \pm 1$
$\sigma_{CRF}$	(keV)		$3 \pm 1$	$11 \pm 2$
$EW_{CRF}$	(keV)		$14 \pm 3$	
$\tau_{CRF}$				$1.5^{+0.4}_{-0.3}$
$\chi^2_\nu$		1.482 (348)	1.258 (345)	1.122 (345)

<sup>a</sup> Uncertainties at the 90% confidence level for a single parameter.

<sup>b</sup> Flux is in units of  $10^{-2} \text{ photons cm}^{-2} \text{ s}^{-1}$  at 1 keV.

<sup>c</sup> The Ne line complex parameters are taken from [14].

ment function: a blackbody with a temperature  $kT \sim 0.6$  keV and an absorbed power law [15]. A high energy cutoff at  $\sim 20$  keV is also necessary to describe the high energy data [16].

This spectral function describes very well our data, both the single *BeppoSAX* NFIs spectra, and the broad-band spectrum. We used the standard X-ray pulsar cutoff of the form  $\exp[(E_c - E)/E_f]$ , where  $E_c$  and  $E_f$  are the cutoff and folding energy, respectively. The smoother Fermi-Dirac cutoff did not adequately describe the high energy tail. After the inclusion of the Ne line complex at 1 keV [14] we obtained a best fit with a reduced  $\chi^2_\nu$  of 1.482 for 348 degrees of freedom (dof). From the analysis of the residuals we were led to add a cyclotron resonance feature (CRF) at  $\sim 35$  keV. Both a Lorenzian or a Gaussian in absorption model improved the fit, yielding  $\chi^2_\nu$ s of 1.122 and 1.258 for 345 dof, respectively. An F-test shows that the improvement is significant at 99.99%. The fit results are summarized in Table 1 [13]. The search for a possible CRF at  $\sim 19$  keV, as suggested by Pravdo [16], was unsuccessful.

The two CRF models are equivalent: the prob-

ability of chance improvement from the Lorenzian to the Gaussian model is 30%. However, we prefer the Gaussian description of the CRF, because the cutoff energy in the Lorenzian fit is too close to the resonance energy. As it is evident from Table 1, the Lorenzian model approximates the fall-off of the spectrum by increasing the cutoff energy, and shifting the cyclotron energy at values lower than those obtained by an absorption Gaussian. This is a known effect already observed for the CRF in Her X-1 [17] and Vela X-1 [18].

Our data do not show the presence of an Iron K-shell line in 6.4–6.9 keV: the upper limit on its equivalent width is 21 eV, slightly more stringent than the 33 eV value obtained by ASCA [19].

The total 0.1–100 keV X-ray luminosity is  $6.6 \times 10^{34} \text{ erg s}^{-1} d_{kpc}^2$ . The fluxes in the bands 0.5–10 and 10–100 keV are  $1.5 \times 10^{-10}$  and  $3.9 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}$ , respectively.

#### 4. TIMING ANALYSIS

The pulse period referred to the Solar System barycenter is  $7.66790 \pm 0.00005 \text{ s}$ , in agreement

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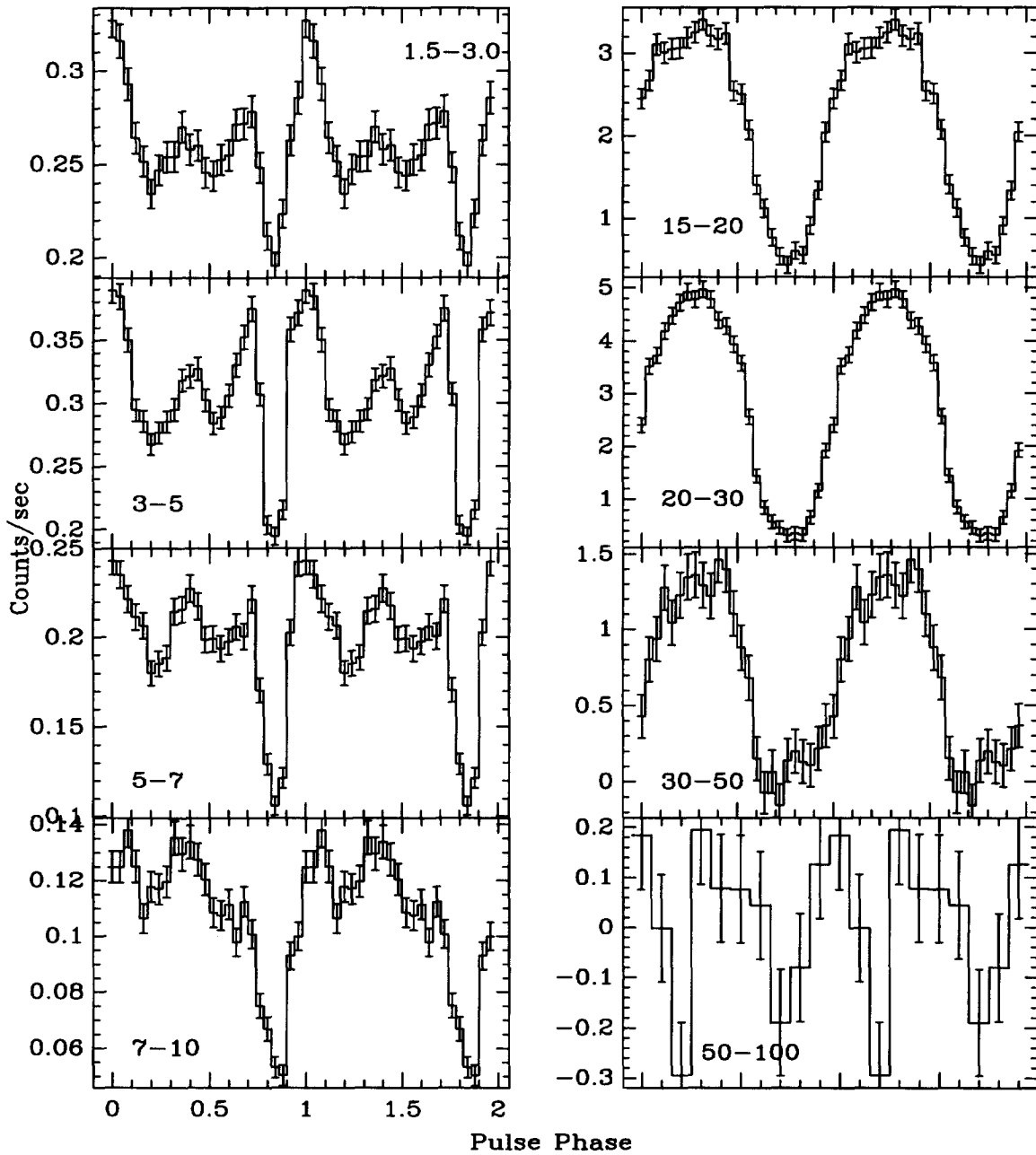


Figure 1. 4U1626-67 pulse profiles as a function of energy observed by the MECS and PDS instruments aboard *BeppoSAX*. Note the transition between the *bi-horned* shape to the almost sinusoidal form, attained with the increase of the interpulse between the two *horns* as the energy increases.

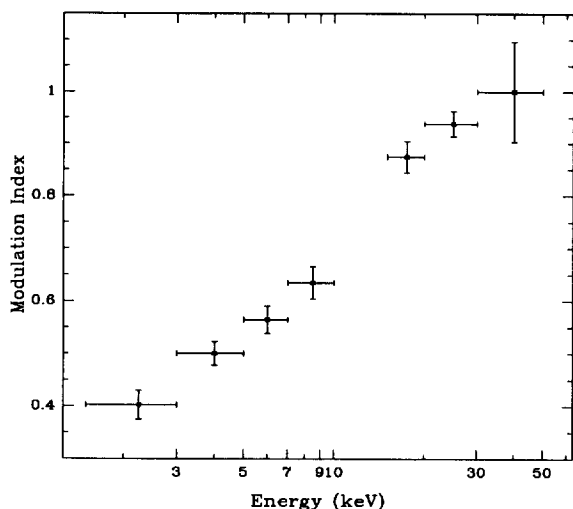


Figure 2. The modulation index as a function of energy computed from the 4U1626-67 pulse profiles shown in Fig. 1.

with BATSE results [20]. We folded the *Bep-poSAX* MECS and PDS data in different energy bands with this period, and the results are plotted in Fig. 1. We confirm the strong energy dependence of the 4U1626-67 pulse profile. The 2-10 keV pulse shape presents the characteristic *bi-horned* form, but the interpulse is not as flat as previously observed: it shows the presence of a small peak. As the energy increases, this third peak increases until it completely fills the interpulse, and the pulse profile becomes sinusoidal. This is a clear indication of the anisotropy in the radiative transfer in the strong neutron star magnetic field [21].

We also computed the so-called *modulation index*, defined  $\Phi(E) = 1 - I_{\min}(E)/I_{\max}(E)$  where  $I_{\max}$  is the maximum intensity in the pulse profile and  $I_{\min}$  is the minimum, at the given energy  $E$ . This index gives information on the dependence on energy of the process which determines the modulation [22]. The advantage of using the modulation index instead of the pulse fraction is that the former does not require the determination of the average emission. The result is shown in Fig. 2, where we can see a monotonic increase of the index with energy.

## REFERENCES

1. Rappaport S., Markert T., Li F.K., et al. *ApJ*, 217, L29, 1977.
2. McClintock J.E., Canizares C.R., Bradt H.V., et al. *Nat*, 270, 320, 1977.
3. Levine A., Ma C.P., McClintock J., Rappaport S., et al. *ApJ*, 327, 732, 1988.
4. Verbunt F., Wijers R.A.M.J., and Burm H.M.G. *A&A*, 234, 195, 1990.
5. Ilovaisky S.A., Motch C., and Chevalier C. *A&A*, 70, L19, 1978.
6. Middleditch J., Mason K.O., Nelson J.E., and White N.E. *ApJ*, 244, 1001, 1981.
7. Chakrabarty D. *ApJ*, 1997. *Astro-ph/9706049*.
8. Jager R., Mels W.A., Brinkman A.C., et al. *A&AS*, 1997. in press.
9. Parmar A.N., Martin D.D.E., Bavdaz M., et al. *A&AS*, 122, 309, 1997.
10. Boella G., Chiappetti L., Conti G., et al. *A&AS*, 122, 327, 1997.
11. Manzo G., Giarrusso S., Santangelo A., et al. *A&AS*, 122, 341, 1997.
12. Frontera F., Costa E., Dal Fiume D., et al. *A&AS*, 122, 357, 1997.
13. Orlandini M., Dal Fiume D., Frontera F., et al. *ApJ*, 1997. submitted.
14. Owens A., Oosterbroek T., and Parmar A.N. *A&A*, 324, L9, 1997.
15. Kii T., Hayakawa S., Nagase F., Ikegami T., and Kawai N. *PASJ*, 38, 751, 1986.
16. Pravdo S.H., White N.E., Boldt E.A., et al. *ApJ*, 231, 912, 1979.
17. Dal Fiume D., Orlandini M., Cusumano G., et al. *A&A*, 1998. *Astro-ph/9711295*.
18. Orlandini M., Dal Fiume D., Frontera F., et al. *A&A*, 1998. *Astro-ph/9711215*.
19. Angelini L., White N.E., Nagase F., et al. *ApJ*, 449, L41, 1995.
20. Bildsten L., Chakrabarty D., Chiu J., et al. *ApJS*, 113, 1997. *Astro-ph/9707125*.
21. Kii T., Hayakawa S., and Nagase F. *Ap&SS*, 118, 375, 1986.
22. Frontera F. and Dal Fiume D. In *Proc. 23<sup>rd</sup> ESLAB Symposium on Two Topics in X-ray Astronomy. 1. X-ray Binaries*, page 57. ESA Publications Division, SP-296, 1989.