BeppoSAX observation of the X–ray binary pulsar Vela X–1

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Abstract. We report on the spectral (pulse averaged) and timing analysis of the \( \sim 20 \) ksec observation of the X–ray binary pulsar Vela X–1 performed during the BeppoSAX Science Verification Phase. The source was observed in two different intensity states: the low state is probably due to an erratic intensity dip and shows a decrease of a factor \( \sim 2 \) in intensity, and a factor 10 in \( N_H \). We have not been able to fit the 2–100 keV continuum spectrum with the standard (for an X–ray pulsar) power law modified by a high energy cutoff because of the flattening of the spectrum in \( \sim 10–30 \) keV. The timing analysis confirms previous results: the pulse profile changes from a five-peak structure for energies less than 15 keV, to a simpler two-peak shape at higher energies. The Fourier analysis shows a very complex harmonic component: up to 23 harmonics are clearly visible in the power spectrum, with a dominant first harmonic for low energy data, and a second one as the more prominent for energies greater than 15 keV. The aperiodic component in the Vela X–1 power spectrum presents a knee at about 1 Hz. The pulse period, corrected for binary motion, is 283.206 \( \pm 0.001 \) sec.

INTRODUCTION

Vela X–1 is the prototype of the class of accreting high-mass X–ray binary pulsars, with a spectrum that was fit by a power law modified at high energy by an exponential cutoff [17]. Moreover, the spectrum shows line features: a \( \sim 6.4 \) keV Iron fluorescence emission line, and a cyclotron resonance feature (CRF) at \( \sim 55 \) keV [14]. The pulse-averaged spectrum depends on the 8.96 day orbital period [8]: episodes of strong absorption are explained in terms of accretion [2] or photoionization [10] wakes.

The pulse period history of the 283 sec X–ray binary pulsar Vela X–1 shows a typical wavy behavior [12]. The reversal of spin-up and spin-down has been explained
in terms of a (temporary) accretion disk, acting as reservoir for the momentum transfer [1].

**OBSERVATION**

BeppoSAX is a program of the Italian Space Agency (ASI) with participation of the Netherlands Agency for Aerospace Programs (NIVR). It is composed by four co-aligned Narrow Field Instruments (NFIs) [3], operating in the energy ranges 0.1–10 keV (LECS, not operative during this observation) [15], 1–10 keV (MECS) [4], 3–120 keV (HPGSPC) [11] and 15–300 keV (PDS) [7]. Perpendicular to the NFI axis there are two Wide Field Cameras [9], with a 40° × 40° field of view.

During the BeppoSAX Science Verification Phase (SVP) Vela X–1 was observed on 1996 July 14 from 06:01 to 20:54 UT, corresponding to orbital phases 0.28–0.35 [6]. All the instruments were operated in direct modes, which provide information on each photon. The two mechanical-collimated instruments were operated in rocking mode with a 96 sec stay time for HPGSPC and 50 sec stay time for PDS. The first part of the observation, about 40% of the total, was characterized by a lower flux and a higher absorption — the 6–40 keV flux passed from 0.34 to 0.64 photons cm$^{-2}$ sec$^{-1}$ in the two states. This is probably due to the passage of the neutron star through clumpy circumstellar material [16].

**SPECTRAL ANALYSIS**

In Fig. 1 we show the results of the spectral fit to the 2–100 keV Vela X–1 spectrum with the usual (for an X-ray pulsar) power law modified by a high-energy cutoff [17]. We added to the model an Iron emission line and a CRF at ∼55 keV. The spectral results are summarized in Table 1, from which it is evident that this model is not able to adequately describe the complex Vela X–1 continuum, and in particular the flattening of the spectrum in the 10–30 keV. A fit with two power laws modified by an exponential cutoff — the so-called NPEX model — is able to describe this flattening [14], although a more detailed model is needed. It is noteworthy that it is in this energy range that the pulse shape changes dramatically from a five to a two peak structure.

**TIMING ANALYSIS**

Each photon arrival time was corrected to the solar system barycenter in order to decouple effects due to Earth and satellite motion. We then defined a *fiducial point* in the pulse profile — the minimum between the two main peaks — and determined the arrival times corresponding to these points. Those points were then fit with a line corrected for the Doppler delays due to the orbital motion (we assumed the ephemeris given by [6]). We find a pulse period of 283.206 ± 0.001 sec
FIGURE 1. BeppoSAX wide-band 2–100 keV spectrum of Vela X–1 during the LOW state. The continuum has been modelled by a power law modified by a high energy cutoff [17]. The inclusion of an Iron emission line and a CRF at \( \sim 55 \text{ keV} \) was not able to describe the data, in particular the flattening in the 10–30 keV range.

TABLE 1. Fit results to the Vela X–1 spectra for both the two intensity states. The continuum has been modelled with a power law modified by a high energy cutoff [17]. All quoted errors represent 90% confidence level for a single parameter.

|                     | LOW State       | HIGH State      |
|---------------------|-----------------|-----------------|
| wabs (cm\(^{-2}\)) | 7.86 ± 0.09     | 1.63 ± 0.03     |
| PhoIndex            | 1.23 ± 0.07     | 1.12 ± 0.04     |
| cutoffE (keV)       | 24.3 ± 0.1      | 24.74 ± 0.07    |
| foldE (keV)         | 13.4 ± 0.1      | 12.11 ± 0.06    |
| LineE (keV)         | 6.44 ± 0.02     | 6.47 ± 0.02     |
| Sigma (keV)         | 0.21 ± 0.04     | 0.20 ± 0.02     |
| Ecyc (keV)          | 55.4 ± 0.5      | 55.9 ± 0.3      |
| Width (keV)         | 10 (fixed)      | 10 (fixed)      |
| Depth               | 2 (fixed)       | 5.3 ± 0.5       |
| \( \chi^2 \)\_dof (dof) | 2.9 (334)      | 9.0 (335)       |
FIGURE 2. Vela X–1 pulse profiles as observed by the three operative NFIs aboard BeppoSAX. From left to right: 2–10 keV (MECS3), 6–40 keV (HPGSPC), 20–100 keV (PDS).

FIGURE 3. Results of the Fourier analysis performed on the PDS data. On the left we show the power spectrum in linear scale, in order to better enhance the effects due to the coherent component (harmonics are shown with dotted lines). The second harmonic is the most prominent because of the double-peak structure of the pulse profile at this energy. On the right we show the same data in a logarithmic scale, in order to evidence the aperiodic component. Note the knee at $\sim 1$ Hz.
for $T_o = 2, 450, 288.5$ JD. In Fig. 2 we show the pulse profile as determined from the three operative NFIs instruments. It is noteworthy the dramatic change of pulse shape from low (five peaks) to high (two peaks) energy, with the transition clearly visible in the HPGSPC data.

We also performed a Fourier analysis on the data, and the results are shown in Fig. 3 for the PDS data. From the point of view of the coherent component, we find that the second harmonic is more pronounced than the first because in this energy range the pulse is double-peaked. For low energy data this behavior is reversed. For what concerns the aperiodic component, we find a sort of knee at about 1 Hz, indicating a $\sim 1$ sec time scale typical of processes that occur at the magnetospheric limit. This result is very similar to that obtained by EXOSAT [5], in which a bump at $\sim 1$ Hz and a high frequency cutoff was observed.

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