INTEGRAL/IBIS OBSERVATIONS OF VELA X-1 IN A FLARING STATE

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ABSTRACT

The wind-accreting X-ray binary pulsar Vela X-1 has been observed by *INTEGRAL* during two extended periods in 2003 as part of the Core Program observations of the Vela region. Here we report about the timing behaviour, particular the intense flaring which happened in Nov/Dec 2003. A preliminary spectral analysis is reported in Kretschmar et al. (2004).

Several flares, typically of duration of the order of one hour, have been observed with intensities corresponding to several Crab. Although Vela X-1 is known to be a very variable source, these types of flares are unusual, both from an observational point of view and with respect to the source itself.

The rotational period of the neutron star is clearly visible, mostly even in resolving individual pulse trains (within flares to a resolution of one sec). The measured pulse periods are 283.535 ± 0.005 s and 283.510 ± 0.005 s for June/July 2003 and Nov/Dec 2003, respectively.

Both, the spectra and the value for the fractional pulsed flux appear to be basically the same inside and outside the flares. We suspect that these flares are simply events of drastically enhanced accretion, probably due to the neutron star meeting dense clouds or blobs of material in the highly structured circumstellar material of the companion with its strong stellar wind.

Key words: pulsars, indvidual: Vela X-1; stars: neutron stars; pulsations; X-rays: binaries; satellites: *INTEGRAL*.

1. INTRODUCTION

Vela X-1 (4U 0900−40) is an eclipsing high mass X-ray binary with an orbital period of 8.96437 days (Barziv et al. 2001) at a distance of ∼2.0 kpc (Nagase 1989) consisting of the B0.5Ib supergiant HD 77581 and a neutron star. The optical companion has a mass of $\sim 23\,M_\odot$ and a radius of $\sim 30\,R_\odot$, while the neutron star mass is estimated to be $\sim 1.8 M_\odot$ (Barziv et al. 2001).

Due to the small separation of the binary system (orbital radius: $1.7\,R_\star$), the neutron star is deeply embedded in the intense stellar wind ($4 \times 10^{-5}\,M_\odot$/yr; Nagase et al. 1986) of HD 77581. X-ray line spectra measurements (Sako et al. 1999) show that this wind is inhomogeneous with dense clumps embedded in a much thinner, highly ionized component. The typical X-ray luminosity of Vela X-1 is $\sim 4 \times 10^{36}$ erg/s, but both, sudden flux reductions to less than 10 % of its normal value (Inoue et al. 1984; Lapshov et al. 1992; Kreykenbohm et al. 1999) and flaring activity (Kendziorra et al. 1990; Haberl & White 1990; Kreykenbohm et al. 1999) have been observed in the past.

The neutron star has a spin period of ∼283 s (McClintock et al. 1976). Both, spin period and its derivative have changed erratically since the first measurement as is observed in many other accreting binary pulsars. The last measurements with the Burst and Transient Source Experiment [1] resulted in a period of ∼283.5 s.

The broadband X-ray spectrum of Vela X-1 has the typical shape found in accreting pulsars: a power law at lower and an exponential cutoff at higher energies. This is further modified by strongly varying absorption which depends on the orbital phase of the neutron star (Kreykenbohm et al. 1999; Haberl & White 1990), an iron fluorescence line at 6.4 keV, and occasionally an iron edge

[1]See `http://www.batse.msfc.nasa.gov/batse/pulsar/data/sources/velax1.html`

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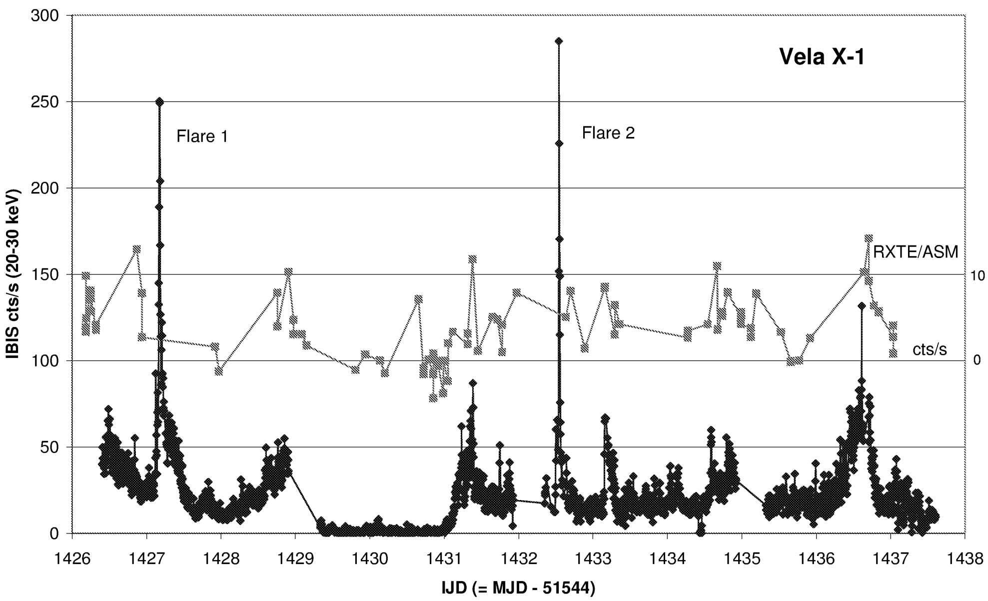

Figure 1. Lower curve: light curve of Vela X-1 in the 20–30 keV range as observed by INTEGRAL/ISGRI during the Nov/Dec 2003 observation. Individual data points are for an integration time of 280 s. Several giant flares are clearly visible (1.0 Crab corresponds to 74 cts/s in 20–30 keV). Upper curve: RXTE/All Sky Monitor count rate from 90 s dwell data (right hand scale). The zero count rate at IJD 1429 to 1431 is due to binary eclipse.

at 7.27 keV (Nagase et al. 1986). A cyclotron resonant scattering feature (CRSF) at ∼55 keV was first reported from observations with *Mir-HEXE* (Kendziorra et al. 1992). Makishima et al. (1992) and Choi et al. (1996) reported an absorption feature at ∼25 keV to 32 keV from *Ginga*. This lower energy feature has been disputed by *BeppoSAX* observations (Orlandini et al. 1998) but supported by phase resolved analysis of *Mir-HEXE* (Kretschmar et al. 1997) and *RXTE* data (Kreykenbohm et al. 2002).

2. OBSERVATIONS AND DATA REDUCTION

The Vela region has been observed as part of the *INTEGRAL* Core Program for extended times in June/July 2003 and in Nov/Dec 2003 (see Table 1). Details about the coverage of binary phases in these two sets of observations can be found in Kretschmar et al. (2004).

As the observations were a raster scan of the whole Vela region in order to support different scientific goals they were not optimized for Vela X-1. This, unfortunately, meant that there are only very few observations of Vela X-1 with *JEM-X* and *OMC*, because of their smaller fields of view.

We have divided the analysis of these Vela X-1 observations in two parts: the spectral analysis, using *ISGRI* and *SPI* data, and the timing analysis. First results of the spectral analysis are reported in Kretschmar et al. (2004). In this paper we concentrate on timing analysis. For this we have produced light curves of Vela X-1 with a resolution of 20 s in three energy bands (20–30 keV, 30–40 keV and 40–60 keV) for all 2003 data (using the *OSA 3* release of the scientific analysis software). For part of the Nov/Dec data also light curves with a resolution of 1 s were generated. All time stamps in these basic light curves were barycenter corrected.

Table 1. INTEGRAL observations of Vela X-1 in 2003

	June/July 2003	Nov/Dec 2003
INTEGRAL Rev	82 - 88	137 - 140
Dates	16 June - 05 July	26 Nov - 08 Dec
IJD (=MJD-51544)	1262.7 - 1282.3	1426.4 - 1437.6
MJD Start	52806.7	52970.4
MJD Stop	52826.3	52981.6
elapsed time	19.6 days	11.2 days
on-source	854 ksec	757 ksec

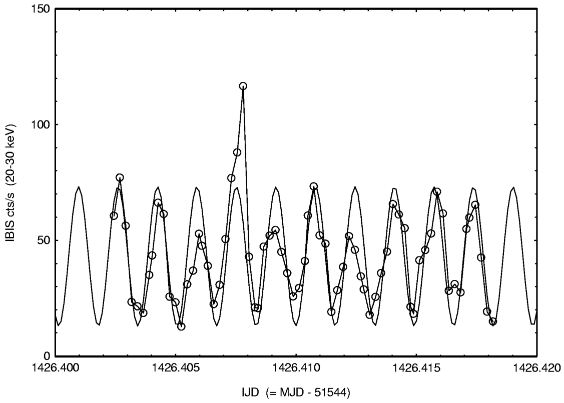

Figure 2. Example of a few 283 s pulse trains (20 s integration per data point) typical for the times outside flares and a crude fit by a double sine curve. Such pulse trains could be followed throughout the entire observations (19.6 days in June/July 2003, 11.2 days in Nov/Dec 2003), allowing for the high precision of measuring the pulse period.

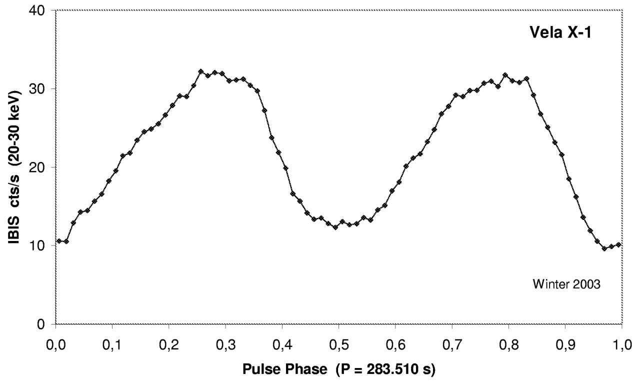

Figure 3. Vela X-1 average pulse profile (20–30 keV) for the Nov/Dec 2003 observation (including flare data) The folding period is 283.510 s.

3. FIRST RESULTS

3.1. The 283 s pulsation and accurate pules period

Both data sets (June/July and Nov/Dec 2003) are of exceptional quality: such (quasi)continuous observations of Vela X-1 for durations of the order of 10 to 20 days with instruments providing good imaging quality, high time resolution and high spectral resolution have never been done before. Because of the extreme time variability and the occurence of two giant flares (besides several other strong flares) we concentrate mostly on the data set from Nov/Dec 2003.

Using the originally produced light curves with 20 s resolution, the pulsational modulation is very evident. During most of the time, individual pulse trains can be clearly followed. An example from the beginning of the Nov/Dec observation with about 5 pulse trains is shown in Fig. 2. Individual data points are for 20 s integration time. The solid curve is a fit to the data with a sine curve of $\sim$141 s, since Vela X-1 has a double peaked pulse profile with the two peaks separated by $\sim$180 degrees.

The time stamps in the original (barycenter corrected) light curves were corrected for binary motion using the ephemeris given for Vela X-1 by van Kerkwijk et al. (1995). A regular period search (by folding the data with different trial periods and searching for the period giving the maximum chi-squared of the resulting pulse profile against a constant) resulted in a period of 283.5 s for the Nov/Dec 2003 data. The accuracy of the period determination was significantly improved by tracing the pulse trains throughout the entire 11.2 days of observation. The following procedure was used: the absolute time of zero phase of a double sine curve is established by a formal fit at the beginning of the light curve, then, choosing a particular pulse period, the absolute time of zero phase at the end of the light curve is predicted and compared to the data. A shift of order 15 s between prediction and data can securely be detected, corresponding to a conservative uncertainty of 0.005 s (15 s/(11.2 days/283.5 s)). There is probably some room for a further increase in accuracy. The same method has been applied to the June/July 2003 data. Using this method, we find the following pulse periods and associated uncertainties:

June/July 2003, JD 245 2817.5: P = 283.535 $\pm$ 0.005 s,
Nov/Dec 2003, JD 245 2976.5: P = 283.510 $\pm$ 0.005 s.

There is no indication of a change in pulse period during or after a large flare.

By folding the entire 20–30 keV data set of the Nov/Dec 2003 observation (including the flares, but excluding the time of binary eclipse) with the period of 283.510 s, the average pulse profile shown in Fig. 3 is derived. In agreement with previous observations, the profile is found to be a simple double pulse, very close to a double sine curve, with the following characteristics: the first ('main') pulse is slightly larger than the second pulse; the leading edge of the second pulse is slightly steeper than that of the main pulse; and the flux between the two pulses (at phase 0.5) is slightly larger than the flux at phase zero; the two peaks are separated by 0.5 in phase. Further analysis will investigate the dependence of the shape of the profile on photon energy. It is known that Vela X-1 has a much more complicated pulse shape at lower energies which we will hopefully be able to determine from the few available *JEM-X* data.

The pulse profile in Fig. 3 contains all data from the Nov/Dec 2003 observation, including all flares. The exclusion of flare data does not result in a different pulse shape.

3.2. The flares in Nov/Dec 2003

In comparing the light curves of Vela X-1 of June/July 2003 and Nov/Dec 2003, one finds that the source was relatively quiet during June/July, but extremely active in Nov/Dec. We therefore concentrate in this contribution on the analysis of the data from Nov/Dec 2003.

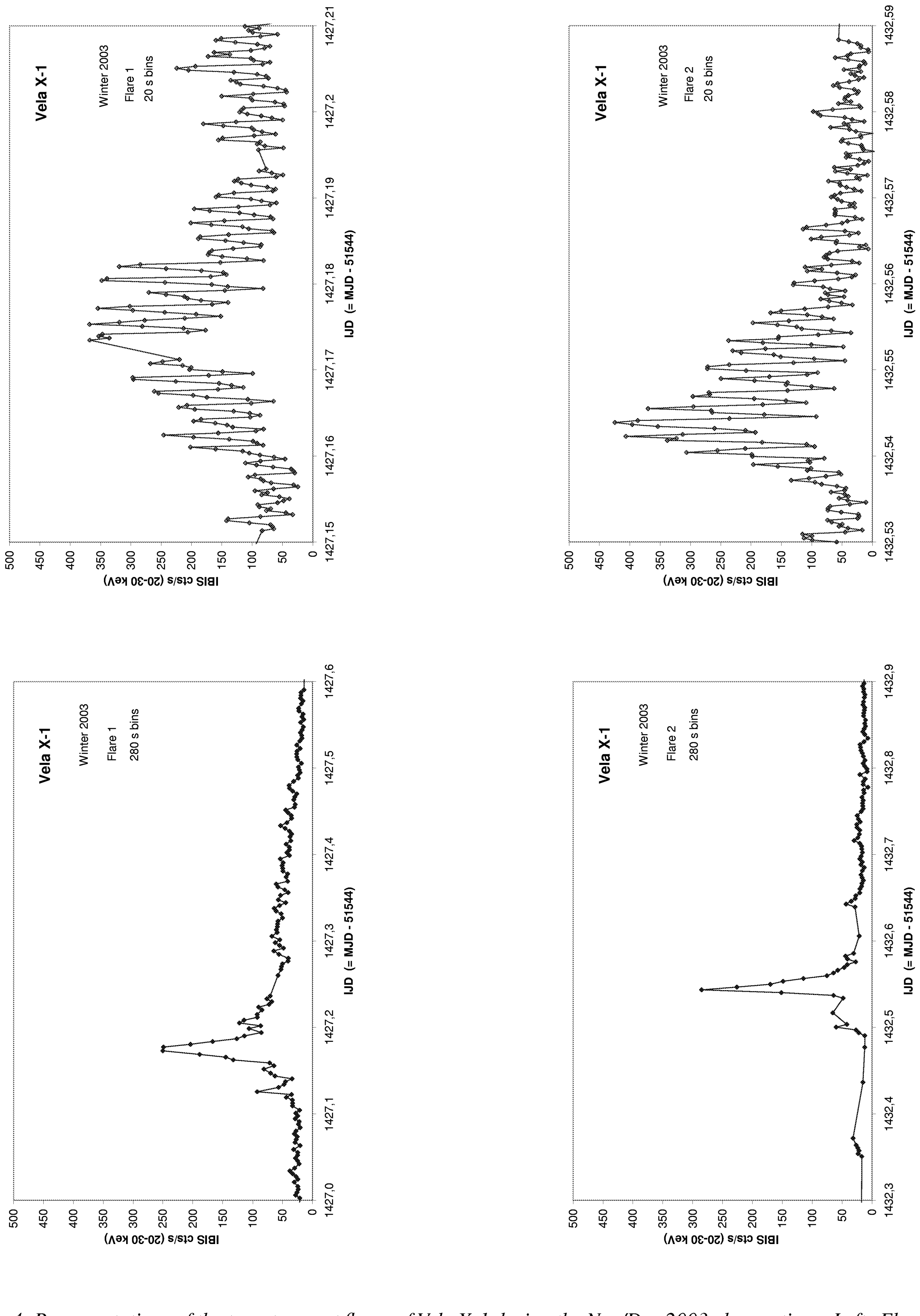

Figure 4. Representations of the two strongest flares of Vela X-1 during the Nov/Dec 2003 observations. Left: Flare 1 and Flare 2 embedded in light curves over 0.6 days with a resolution of 280 s per data point. Right: Flare 1 and Flare 2 on a 10 times expanded time scale (1.44 h) with a resolution of 20 s per data point. The 283 s pulsation is clearly seen. (Note that the count rate scale is the same left and right).

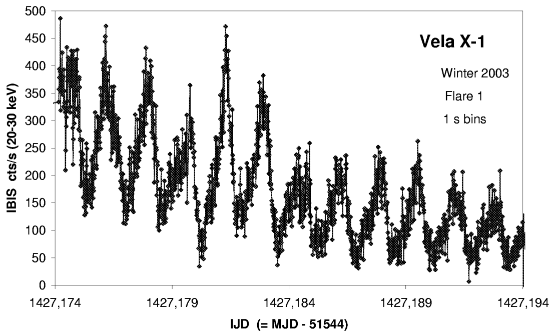

Figure 5. Part of Flare 1 plotted with a resolution of 1.0 sec per data point.

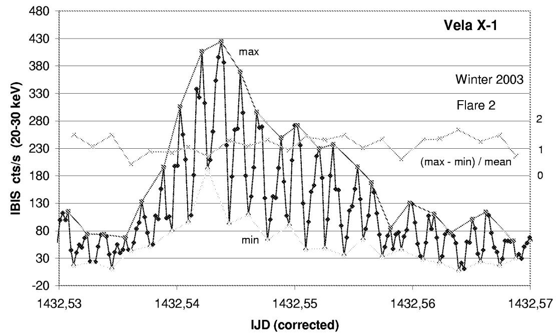

Figure 6. Flare 2 of the Nov/Dec 2003 Vela X-1 observation. The peak-to-peak modulation is compared to the mean count rate: (max - min / mean) is roughly constant around 1.0 (right hand scale). The degree of modulation is not changed during the flare.

Fig. 1 shows the light curve of Vela X-1 for the Nov/Dec 2003 observation in the 20–30 keV range. Individual data points correspond to an integration time of 280 s. This integration time, very close to the pulsational period, was deliberately chosen in order to separate the regular pulsational modulation from the mostly erratic variations on longer time scales. We identify two giant flares (Flare 1 and Flare 2) which reach a photon flux corresponding to 3.4 and 3.8 times that of the Crab, respectively (with an integration time of 280 s). The flux of the Crab in *ISGRI* in the 20–30 keV range using the same method of analysis as for Vela X-1 was found to be 74 cts/s. In addition, several other – less spectacular but still strong – flares (reaching ∼1 to 2 Crab) are seen. The 'normal' 20–30 keV flux of Vela X-1 is around 22 cts/s (300 mCrab).

Also shown in Fig. 1 is the '90 min dwell' light curve as observed by the All Sky Monitor (ASM) on RXTE[2]. It is clear from this graph that the RXTE/ASM has entirely missed the two giant flares and most of the action of the other strong flares. By comparing the two light curves one can identify some of the high points in the ASM light curve as being associated with one of the other flares covered and resolved by *INTEGRAL*.

Detailed light curves of the two giant flares are shown in Fig. 4 . Left: 0.6 day light curves with a resolution of 280 s, right: 0.06 day light curves with a resolution of 20 s. Although the detailed shapes of the two flares are different, the duration of the main parts of the flares is quite similar: of the order of 1 hour. This is less than 0.005 of one binary revolution and corresponds to just about one dozen neutron star rotations. In Flare 2 the rise time is about two NS revolutions, and the decay time is about five NS revolutions. In Flare 1 both, rise and decay are about a factor of two slower. In both flares there are indications for small precursors. While Flare 2 dies out with one short decay constant, Flare 1 appears to have a tail with a second, slower decay, more than an order of magnitude longer than the main decay.

If a resolution of 20 s is chosen (as in the right hand side of Fig. 4), the pulsations inside the flares are resolved with high statistical significance. With the observed count rate of up to nearly 500 cts/s even light curves with a resolution of 1 sec are far from being dominated by statistical noise, as is evident in Fig. 5, showing part of Flare 1. Note that, due to the short term variability on time scales of a few to several sec, the maximum observed count rates increase with decreasing integration times: the maximum count rate seen in Fig. 5 of 480 cts/s corresponds to flux of 6.5 times that of the Crab. The normal luminosity of Vela X-1 is $\sim 4 \times 10^{36}$ ergs/s. In the peak of the two giant flares it reaches ∼10 times this value with integration times of 280 s (the duration of one pulse), or ∼20 times this value with integration times of 20 s. That means that even in the peaks of the giant flares the source does not enter into the super-Eddington regime of accretion.

Also evident from Fig. 5 is the strong pulse-to-pulse variability which was first noticed in Vela X-1 by Staubert et al. (1980). A visual inspection of large parts of the available *INTEGRAL* data consistently show pulse-to-pulse variations with respect to amplitude, shape and phase. A detailed future analysis will quantify this behaviour.

As already mentioned above, besides the two giant flares, several less spectacular, but still sizable flares of Vela X-1 can be identified in Fig. 1 (e.g. at IJD 1426.5, 1431.3, 1433.2, 1436.7, reaching ∼1 Crab or more (at 280 sec integration). If one uses the integrated counts instead of the maximum count rate to characterize the flare, some of the other flares may even be considered 'stronger'. For instance, the flare peaking at 1436.7, has a peak count rate (at 280 s integration) of 'only' 2 Crab, but has an extent of 10 times that of Flare 1 and Flare 2 (∼7 h rise, 4 h decay), and contains 2 times the number of counts as Flare 1 and 3 times that of Flare 2. In further analysis we will investigate the 'sizes' and shapes of the various flares in more detail.

The preliminary spectral analysis of *INTEGRAL* data of Vela X-1 (Kretschmar et al. 2004) has shown that despite

[2] See `http://xte.mit.edu/ASM_lc.html`

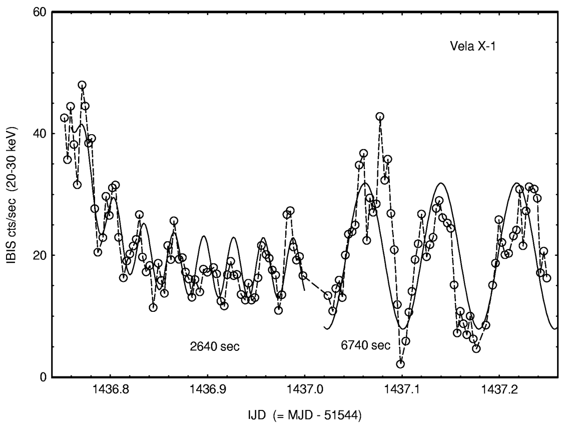

Figure 7. A special part of the light curve of Vela X-1 of the Nov/Dec 2003 observation. In these data quasi periodic modulations lasting for a few cycles are apparent. The periods are around 2640 s and 6740 s, respectively. The dotted line connects the data points (280 s integration), the solid line is the best fit sine curve (with an additional exponential component for the left train).

the rapid and strong brightening in flares the energy spectrum of the source is not very different from that obtained during more usual flux levels. A similar behaviour is also present for the pulsations. The relative depth of the modulation does apparently not change during flares. This is evident from Fig. 6 which shows Flare 2 again with 20 s resolution. To guide the eye, the maxima of adjacent half-pulses are connected, the same is done with the minima. The relative depth of modulation is formally calculated as the difference between a maximum and the following minimum divided by the mean between the two values ([max-min]/mean). This modulation depth is essentially constant around 1.0 (right hand scale in Fig. 6).

3.3. Search for quasi-periodic modulations

We have undertaken a first search for quasi-periodic modulations on time scales between 2 s and 10000 s. The motivation for this comes from two sources. First: about a dozen accreting binary pulsars with regular pulsations show quasi-periodic oscillations (QPOs) in addition to the regular pulsation (Shirakawa & Lai 2002). Second: In working with the Nov/Dec 2003 light curves of Vela X-1 the educated eye finds in several stretches of data indications for variations which appear quite regular and inconsistent with a pure stochastic behaviour.

To give an example for this type of variation, we show Fig. 7 where there appear to be two quasi-periods present: the left part of the data can be well described by a modulation with a period of 2640 s, the right part - even more convincing - is modulated by 6740 s. To guide the eye, the respective best fit sine curves are shown (the statistical uncertainties of the data points are of the order of the size of the symbols). Formal chi-square searches clearly find the respective periods. Also, first searches for QPOs using the method of dynamical Power Spectral Density distributions (PSDs) have found some candidate stretches of data. However, since it is well known, that red noise can, with non-negligible probability, indeed produce flux modulations of quasi-periodic nature, more quantitative tests need to be performed. As an example for the danger of over-interpretation see the discussion of the variability of Mrk 766 by Benlloch et al. (2001).

For Vela X-1 one might expect to find QPOs in the period range of 10 to 40 s, due to its close similarity to 4U 1907+09. This binary pulsar powered by accretion from stellar wind has a binary period of 8.38 d and a pulsational period of 440 s. In't Zand et al. (1998) reported the detection of a 1 hour long episode during which this source showed oscillations with a period of 18 s. Our search for Vela X-1 sofar has not turned up any persistent periodic modulations at periods shorter than 140 s, half the regular pulse period (there appears to be some power at 70 s) or any short period quasi-periodic oscillations present over some period of time. The establishment of formal upper limits requires further work. We will systematically search all Vela X-1 data for events similar to that reported from 4U 1907+09.

4. SUMMARY

The two sets of core program observations of Vela X-1 by *INTEGRAL* in 2003 are of great value for the understanding of this source. To a large extent this is due to the capabilities of the *INTEGRAL* observatory, which simultaneously provides good imaging, good spectral resolution, high time resolution and - due to its 3 day, highly excentric orbit - the extremely useful capability of performing long, uninterrupted observations.

It is further highly appreciated that the source cooperated by entering an extremely active period during the Nov/Dec observations, displaying a high degree of variability, including two giant flares and several other (still strong) flares. The data contain a great deal of information with respect to both the spectral and the timing behaviour. These data can be considered the first ever, allowing the spectral resolution of a Cyclotron Resonant Scattering Feature. Likewise, the timing data, particular during the giant flares, are without previous precedents. Clearly, the most information about the physics in this object will result from the combined spectral and timing analysis.

Unfortunately, the scheduling of these observations was not optimum for Vela X-1, so we miss potentially very valuable data from *JEM-X* at low X-ray energies and from the *OMC* in the optical range. Both is regrettable since the strong activity in X-rays is suspected to be due to increased stellar wind mass loss of the optical companion. *JEM-X* data would have allowed to sample the stellar wind environment by measuring the column density via the low energy X-ray spectrum. On the other hand, Vela X-1 was unneccessarily observed during eclipse.

The first results about the spectral analysis is reported by Kretschmar et al. (2004). The 53 keV cyclotron feature is clearly seen and energetically resolved. Further analysis will have to concentrate on detailed pulse phase resolved spectroscopy.

The first results of the timing analysis are the following:

- Pulse periods were measured to a high precision: 283.535 ± 0.005 s for June/July 2003 and 283.510 ± 0.005 s for Nov/Dec 2003. These values are in line with the long-term period development of Vela X-1. There is a slight spin-up from June/July to Nov/Dec 2003, but no indication of spin-up or spin-down during either of the two observations. In particular, no change of the period is observed in connection with a flare.

- While Vela X-1 was relatively calm during June/July 2003, it showed extreme variability during Nov/Dec 2003. Two giant flares with fluxes corresponding to 3.4 Crab (Flare 1) and 3.8 Crab (Flare 2) (20–30 keV, 280 s integration) and several other flares (with $\sim$1 to $\sim$2 Crab) were observed. We interprete these flares as episodes of drastically increased mass accretion which occur when the NS travels through the highly structured stellar wind environment of the optical companion. This environment is known to be highly inhomogeneous and probably contains clouds of material with higher density which at times are intercepted by the accreting NS.

- The modulation depth, defined by (max-min)/mean, stays constant at a value around 1.0 inside and outside flares.

- There are strong pulse-to-pulse variations visible. This is with respect to the amplitude, the shape and the phase of both peaks in the double-peak pulse profile.

- No persistent modulations other than those associated with the NS rotation of 283 s have been found.

- The search for QPOs was not successful sofar, except for the detection of some stretches in the light curve of Nov/Dec 2003 which seem to show systematic variations, apparently inconsistent with pure stochastic variations. However, these events are of transient nature and contain only a few cycles. As an example, the three cycles with an apparent period of $\sim$6700 s shown in Fig. 7 may represent a quasi-periodic density structure of the material through which the NS travels on its tight orbit around the mass loosing companion.

A more detailed and systematic analysis of the available *INTEGRAL* data of Vela X-1 is underway with respect to both spectral and timing analysis and its combination, e.g. phase resolved spectroscopy and the description of overall timing properties which may be energy dependent.

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