

# INTEGRAL OBSERVATIONS OF THE VELA REGION FOCUSING ON VELA X-1

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## ABSTRACT

The Vela region has been observed for 1.7 Ms in November 2005 by the INTEGRAL satellite. We present preliminary spectral and temporal results of Vela X-1, an eclipsing neutron star hosted in a wind-accreting high-mass X-ray binary system. Using data from ISGRI, SPI and JEM-X, we firmly confirm the existence of cyclotron resonant scattering features (CRSF) at  $\sim 27$  keV and  $\sim 54$  keV, implying a neutron-star magnetic field of  $3 \times 10^{12}$  Gauss, and the presence of an iron emission line at  $\sim 6.5$  keV. During two strong flares those parameters remained unchanged. Furthermore we measure the neutron-star spin period of 283.6 s, indicating a still constant trend.

## 1. INTRODUCTION

The Vela region has been observed by INTEGRAL [1], ESA's gamma-ray satellite, in the frame of our accepted AO-3 open-time proposal. Data were taken from November 4 to December 4, 2005, during 1.7 Ms, from INTEGRAL revolution n°373 to 383, in 473 different pointings. The key target is the detection of  $\gamma$ -rays emitted by the decay of radioactive isotopes produced in stellar nucleosynthesis processes as e.g. 1809 keV emission from  $^{26}\text{Al}$  decays. Results of the  $^{26}\text{Al}$  studies are presented in [2]. Besides nucleosynthesis studies, the region is also of interest for the presence of several point sources, among which Vela X-1, for which we present preliminary results in this paper.

In the soft  $\gamma$ -ray band the brightest point source in the region is Vela X-1, an eclipsing wind accreting high-mass X-ray binary system (HMXB) consisting of a neutron star (NS) and a massive, 23 solar masses ( $M_{\odot}$ ), donor star (HD 77581) classified as a B0.5 super-giant [3]. The system has an orbital period of 8.964 days [4]. The NS is deeply embedded in the intense stellar wind of the companion, whose inferred mass-loss rate is of the order of  $10^{-7} M_{\odot}/\text{yr}$  [5]. The NS shows a spin period of  $\sim 283$  s in X-rays (e.g. [6]).

## 2. SEARCH FOR SOURCES IN VELA REGION

Using the full IBIS/ISGRI data set, we search for point sources in the Vela region, by constructing a mosaic image of the region (Fig. 1) in the 18-60 keV energy range, most suited for new source detection. The

sources found comprise four sources (Tab. 1) –all of them known– which are detected with significance above  $6 \sigma$ , considered to be the limit for firm source detection.



Fig. 1. Image of the Vela region by ISGRI (18-60 keV).

Source	$\sigma$ -level
Vela X-1	1316.3
Vela Pulsar	48.2
H 0918-548	13.9
IGR J09026-4812	12.0
IGR J07597-3842	5.77
GRO J1008-57	5.46
Fairall 1146	5.45
ESO 209-12	5.11
IGR J10109-5746	5.08

Tab. 1. Sources found by ISGRI in the Vela region (18-60 keV energy band, 1.7 Ms exposure). Only the first four sources can be considered firmly detected.

A similar search has been performed with the SPI data. We use SPIROS imaging in the 20-40 keV energy band. The net exposure time was 1 Ms after selecting the best 271 pointings ( $\chi^2 < 10$  in SPIROS). The SPIROS mode used was a blind search for 3 sources. The background model used empty fields close in time to the Vela data taking period, however the saturating Ge-detector background model yields similar results. We obtain a Vela region image (Fig. 2) and the results are summarized in Tab. 2. Two sources, Vela X-1 and

Vela Pulsar, are firmly detected, while the 3<sup>rd</sup> source might be associated with IGR J07597-3842 or IGR J07565-4139, both located within the SPI angular resolution at a distance <math>2^\circ</math> from the detected position.

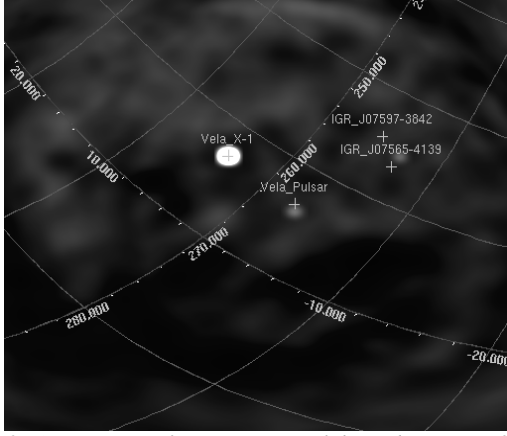


Fig. 2. SPIROS significance image of the Vela region (20-40 keV) obtained in a blind search for three sources.

Source	Sigma	Cat Source	Distance
1	235.1	Vela X1	0°
2	11.6	Vela Pulsar	~0.5°
3	9.7	IGR J07597-3842	~1°
		IGR J07565-4139	~2°

Tab. 2. Sources found by SPIROS (20-40 keV) in a blind search for three sources. The distances of those sources to known sources in the region are listed.

### 3. VELA X-1 LIGHTCURVES

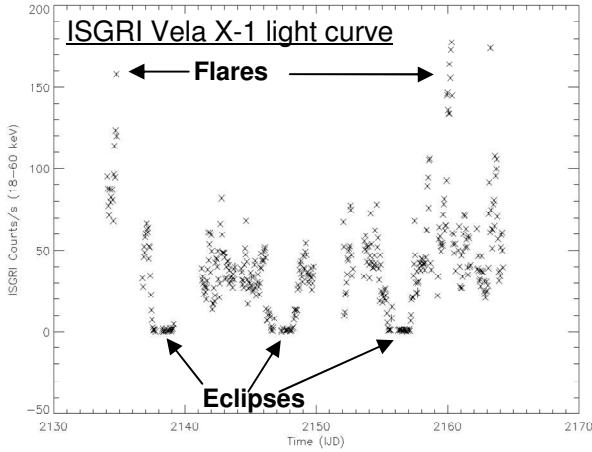


Fig. 3. ISGRI light curve of Vela X-1. Energy 18-60 keV, time bin 1h, time measured in days since January 1<sup>st</sup>, 2000 (IJD).

The Vela X-1 light curves, observed respectively with ISGRI and SPI are shown in Fig. 3 and Fig. 4. Both instruments detect the same Vela X-1 variability, typical for wind accreting pulsars, namely three NS eclipses by the companion star, as well as two strong flares (one in revolution 373 and one in revolution 382).

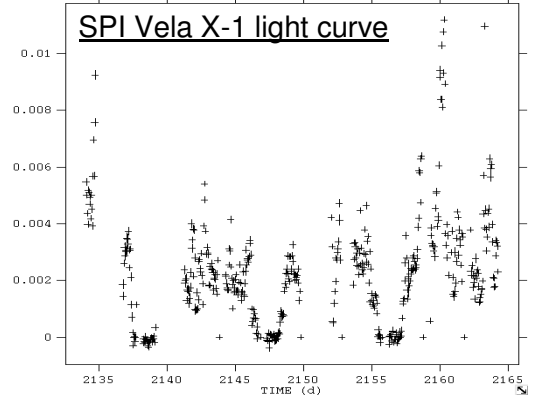


Fig. 4. SPI light curve of Vela X-1 (20-40 keV) in  $\text{ph}/\text{cm}^2/\text{s}$ .

### 4. VELA X-1 FOLDED LIGHTCURVE

Using the barycenter-corrected ISGRI light-curves, spanning over a single pointing (science window) of ~1 h duration, we find the NS spin period to be  $283.6 \pm 0.1$  s, consistent with previous findings [13]. The pulse profiles in two ISGRI energy bands (20-40 keV and 40-100 keV) are shown in Fig. 5. A deeper analysis is ongoing.

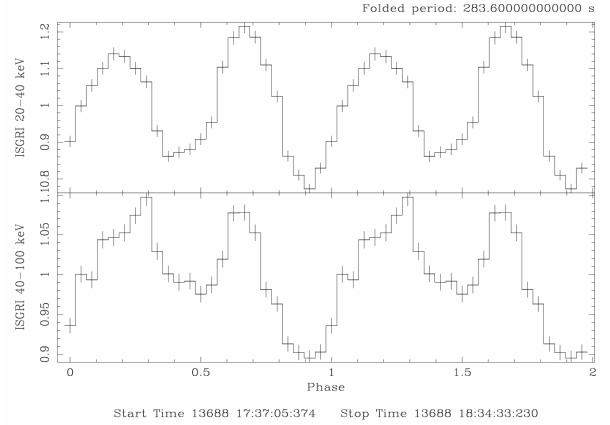


Fig. 5. ISGRI light curve of Vela X-1 folded at the best period of 283.6 s. Two periods are shown for clarity.

### 5. VELA X-1 PERSISTENT AVERAGE SEPCTRA

The presence of two cyclotron resonant scattering features (CRSF) in the average spectrum of Vela X-1 has been debated since a long time in the literature [7-15]. With our analysis we assess the presence of two CRSF with fundamental energy at ~27 keV and the 1<sup>st</sup> harmonic at ~54 keV in agreement with the RXTE observations by Kreykenbohm et al. (2002) [11], and at variance with the single CRSF at ~55 keV reported by La Barbera et al. (2003) [12] using BeppoSAX data. We confirm the real nature of the debated ~27 keV feature, seen independently by the two different instruments ISGRI and SPI.

We derive the persistent average spectrum of Vela X-1, using JEM-X and ISGRI, by removing the time intervals of the two strong flares and the eclipses (80 ks

exposure available for JEM-X, 737 ks for IBIS). The fit with a simple cutoff power law (Fig. 6) displays the presence in the data of residuals at  $\sim 6.5$  keV,  $\sim 27$  keV and  $\sim 54$  keV. We model the low-energy excess with a Gaussian emission line, and describe the two high-energy dips with the cyclotron absorption model cyclabs of XSPEC [16]. This yields a fit with a reduced  $\chi^2$  of 1.2 applying 2% systematics (Fig. 7). We associate the Gaussian emission feature found at 6.44 keV with a Fe emission line. The low-energy cyclotron absorption line is found to be located at  $27.0 \pm 0.3$  keV. Note that the ISGRI/JEM-X inter-calibration factor is around 1.3. Including the SPI data (Fig. 8), the same model yields a fit with a reduced  $\chi^2$  of 1.2 applying 3% systematics, a Fe emission line at 6.56 keV and the low energy cyclotron line located at 27.2 keV.

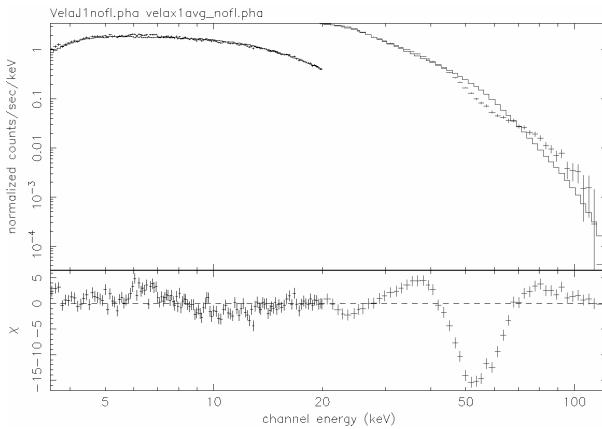


Fig. 6. INTEGRAL JEM-X and ISGRI persistent average spectrum of Vela X-1, fit with a simple cutoff power law. The upper panel shows the data and the best fit model (solid line); the lower panel shows the residuals.

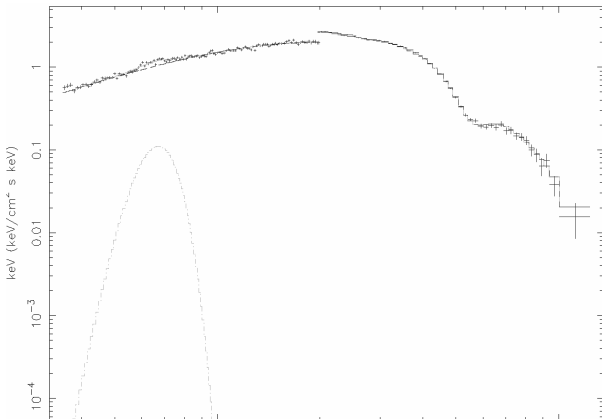


Fig. 7. INTEGRAL JEM-X and ISGRI unfolded persistent average spectrum of Vela X-1.

The Vela X-1 persistent average SPI spectrum using SPIROS is shown in Fig. 9. This spectrum is modeled using constant, cutoff power-law, two CRSF features with energies fixed by  $E_1=E_2/2$  and fluxes modeled by:

$$F_{CRSF}(E) = \exp\left[-\frac{D(WE/E_i)^2}{(E-E_i)^2 + W^2}\right]$$

The result of the fit is shown in Tab. 3 (1<sup>st</sup> data column). The fit using the same model applied to both SPI and ISGRI data, leads to compatible results, shown in Tab. 3 (2<sup>nd</sup> data column).

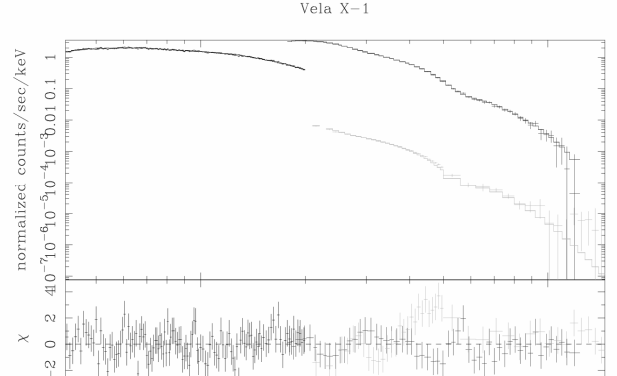


Fig. 8. JEM-X, ISGRI and SPI persistent average spectrum of Vela X-1 (combined fit).

	Persist. avr. SPI	Persist. avr. SPI + ISGRI	In flares SPI
$E_1=E_2/2$	$27.44 \pm 0.43$	$27.88 \pm 0.14$	$27.5 \pm 0.6$
$W_1$	$6.73 \pm 1.6$	$12.09 \pm 0.94$	$5.58 \pm 1.69$
$D_1$	$0.17 \pm 0.052$	$0.28 \pm 0.078$	$0.16 \pm 0.049$
$W_2$	$8.84 \pm 1.96$	$10.86 \pm 1.05$	$8.45 \pm 2.96$
$D_2$	$1.01 \pm 0.12$	$1.1 \pm 0.07$	$0.76 \pm 0.15$
$\chi^2$	1.03	1.9	1.17
ndf	71	90	71

Tab.3. Results of fits to the SPI and SPI+ISGRI persistent average spectra, as well as the SPI spectrum during flares, using the model “constant, cutoff power-law, 2 CRSF (with fixed energy ratios)”.

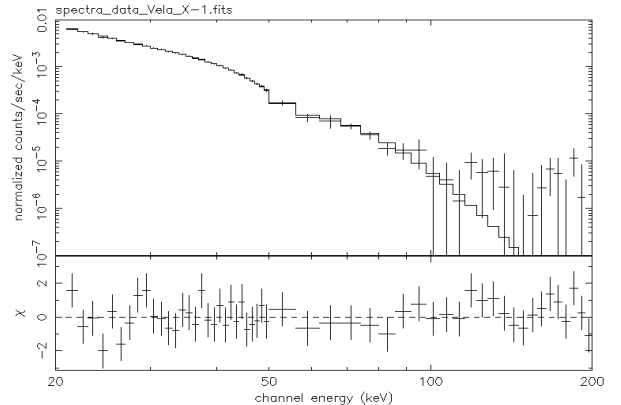


Fig. 9. SPI persistent average spectrum of Vela X-1.

## 6. VELA X-1 SEPCTRA DURING FLARES

For the Vela X-1 flare in revolution 373, one pointing is used to derive the combined JEM-X and ISGRI spectrum, shown in Fig. 10. In this limited dataset, the presence of the Fe emission line is still significant at

~6.5 keV, and the low-energy CRSF feature (fit with cyclabs) is found at  $26.0 \pm 0.4$  keV. For the flare in revolution 382, nine IBIS pointings are used, and the low-energy CRSF feature is found at  $27.0 \pm 0.3$  keV.

The SPI spectrum obtained by combining the flares of Vela X-1 in revolutions 373 and 382 is presented in Fig. 11. The result of the fit using the previously presented model with two CRSF is reported in Tab. 3 (3<sup>rd</sup> data column). We compare those parameters with the ones found for the persistent average spectrum using either SPI alone or SPI+ISGRI data. We conclude that no important change in the structure of the CRSF features can be noticed for those Vela X-1 flares.

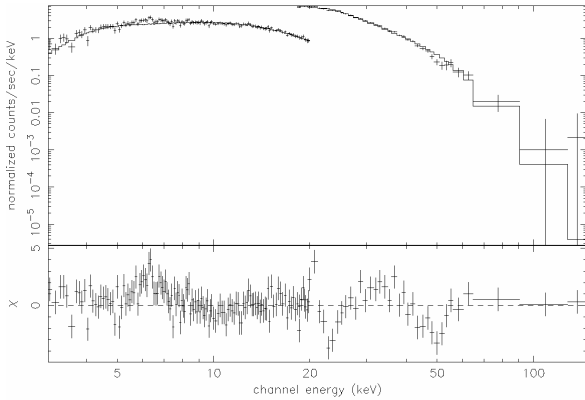


Fig. 10. JEM-X and ISGRI spectrum of Vela X-1 during flare in rev. 373, fitted with a simple cutoff power law, showing the presence of residuals at ~6.5 keV, ~26 keV and ~52 keV.

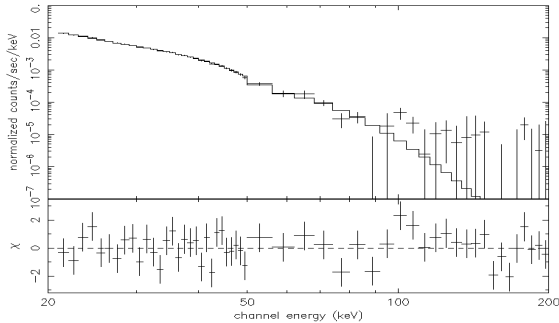


Fig. 11. SPI spectrum of Vela X-1 during flare, fitted with a cutoff power-law and two CRSF.

## 7. CONCLUSIONS

The INTEGRAL satellite observed the Vela region in the X-ray and gamma-ray energy bands during 1.7 Ms between 4<sup>th</sup> November and 4<sup>th</sup> December 2005, from revolution 373 to 383, in the context of our accepted AO-3 INTEGRAL open-time observation. We present preliminary results of the analysis of the ISGRI, SPI and JEM-X data. We focus on a spectral and temporal study of the eclipsing high-mass X-ray binary Vela X-1. Thanks to this long-term observation we derive the time-averaged spectrum of the source and firmly confirm the existence of cyclotron resonant scattering features (CRSF) at ~27 keV and ~54 keV using

IBIS/ISGRI and SPI data separately and in a combined fit. Assuming canonical parameters for the neutron star (mass  $1.4 M_{\odot}$ , radius 10 km), a 27 keV CRSF implies a neutron star magnetic field of  $3 \times 10^{12}$  Gauss. Using the JEM-X data we also found the presence of a Fe emission line at ~6.5 keV. During two strong Vela X-1 flares we found that the energy positions of the CRSF features remain unchanged with respect to their persistent average values. Furthermore we obtain a spin period of 283.6 s by folding the Vela X-1 light curve over one pointing of 1 h duration. In order to complete the Vela X-1 analysis, work is currently ongoing. We will derive a precise orbital ephemeris, which is important for the study of this system, since it allows to determine detailed time-resolved spectra during the eclipse ingress and egress phases in different energy bands, and to monitor details of the companion wind. Orbital and pulse-phase resolved spectroscopy will permit us to understand the underlying physics of the high-energy emission. Using a relativistic description of the polar-cap emission of the neutron star, the variation of the pulse morphology with energy and time will permit to model the pulsed flux in energy and constrain the system geometry.

## 8. REFERENCES

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