A search for variability of hard X-ray emission from the Vela pulsar wind nebula

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Abstract. Observations of hard X-ray emission from the Vela pulsar wind nebula (PWN) with the ISGRI camera aboard INTEGRAL gamma-ray observatory have been analysed with the aim to search for possible flux variability on scales from weeks to years, which could be caused by short-term evolution of pulsar wind structures similar to those governing sharp flares and flux depressions observed in the sub-GeV emission of the Crab PWN. No statistically significant flux depressions or flares have been found in none of the considered energy ranges: 20-50 keV, 50-100 keV, and 100-200 keV, however some hints of flux instability can be seen in the former two bands. If the variability of the pulsar wind termination surface or instabilities of turbulent magnetic field in the nebula predicted by a number of PWN models indeed influence the synchrotron spectrum of such objects, the variability of the 1-30 MeV emission from the Vela PWN could be checked with the next generation of gamma-ray facilities, like eASTROGAM or HERMES.

1. Introduction
Pulsar wind nebulae (PWNe) are efficient sources of accelerated particles and hard emission, which is sometimes observable in the range up to tens of teraelectronvolt (TeV). While such objects have been being studied throughout the electromagnetic spectrum, from the radio band to gamma-rays, already for several decades, many important aspects of their origin, evolution, and structure are still not known. One prominent example is the gamma-ray flaring activity observed in the Crab nebula [1, 2], which has not obtained a clear and univocal physical interpretation as of yet.

Recent studies of gamma-ray variability of the Crab nebula [3, 4] have revealed that along with the flaring activity, the nebula demonstrates month-long periods of 0.1-0.3 GeV gamma-ray flux depressions, short-period (days to weeks) of sharp drops of the gamma-ray flux, and even hints of periodicity in flaring activity with a period around 49 weeks. The authors of [3] have suggested an original interpretation of such phenomena within a model of synchrotron emission generated by relativistic electrons in fluctuating magnetic fields of the nebula. Hence it it natural to look if similar phenomena occur in other PWNe and if they can be as well understood in the frame of the models suggested by [3, 5].

Within this short note we report on an analysis of 1531 exposures of the Vela PWN taken on various dates within the 15-year long period from 2003 and 2018 with the INTEGRAL ISGRI camera. The aim of this study was to search for variability of the hard X-ray flux of the nebula.
in the 20-200 keV range on scales from weeks to years. As the estimated magnetic field in this PWN – \( \sim \mu G \) – is much smaller than that of the Crab nebula (about 200 \( \mu G \)), the expected energy range where the synchrotron emission flux from the pulsar wind electrons and positrons is predicted to be variable should be also shifted down to hard X-rays or MeV range gamma-rays. The spatial resolution of ISGRI with its 6’ pixels is reasonably well suited to study spectral and timing characteristics of the Vela PWN, whose apparent extent in the 0.5-7 keV X-rays is about 4’ (e.g., [6, 7]).

2. Observations and data reduction

Unlike survey instruments, INTEGRAL performs observations according to a sophisticated schedule determined by the particular program set, approved by its time allocation committee. Due to the specifically wide hexagonal pointing pattern of the observatory, particular objects every time appear at various positions of the large field of view (FOV) of the ISGRI camera, only part of which being fully coded [8]. In order to avoid the effects of partially coded FOV, we chose 1531 ISGRI exposures (“science windows”) of Vela PWN, where the object was located not further than 4.5’ from the FOV center. Both of the above have led to a substantially irregular set of exposures, which still allows one to search for flux variability and even for its possibly periodic behaviour.

Reduction and analysis of the selected ISGRI exposures have been performed with the OSA 10.2 package [9]. The data reduction consisted of image deconvolution for each of the individual exposures in each of the three predefined energy bands: 20-50 keV, 50-100 keV and 100-200 keV. Afterwards a global image mosaic was constructed in each of the bands, and all the significantly strong emission sources were iteratively identified on each of the mosaics. This was followed by extraction of spectra of a dozen of most prominent sources in the field of view for each of the individual exposures and construction of the full-band spectrum of the nebula averaged over all the considered exposures, which is shown in Figure 1.

The analysis of the time-averaged spectrum has been performed with XSpec v.12.10 [10]. The spectrum can be described by a power law model with index \( \Gamma = 1.93 \pm 0.02 \) and the 20-40 keV flux of \((4.89 \pm 0.06) \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1} (\chi_{\text{red}} = 1.2/10 \text{ d.o.f.}, \text{the uncertainties are reported at the 90\% confidence level})\), in a good agreement with the fit reported by [11]. One of possible explanations of the moderate quality of the obtained spectral fit is that the true spectral index of the nebula might have varied during the 15 years of observations due to variations of either the particle acceleration efficiency, the magnetic field strength and structure, or both. It should be stressed that the phase-averaged flux of hard X-ray emission observed from the Vela pulsar residing inside the nebula is \( \sim 50 \) times lower than the overall flux mentioned above [11], so the emission measured with ISGRI above 20 keV is indeed dominated by the nebula and all the possible flux variations above a several per cent level can be attributed to the processes in the nebula, and not to a contamination from the pulsar.

With the source spectrum determined in each of the individual exposures, we were able to further compute per-exposure fluxes and their uncertainties in each of the considered energy bands and construct the corresponding light curves. Part of the raw lightcurves covering the time interval between IJD\(^1\) 1425 and IJD 1440 is shown in Figure 1 as an example.

3. Lightcurve analysis

The hard X-ray lightcurves of the Vela PWN measured with the ISGRI camera and consisting of 1531 individual exposures were further analysed to search for possible flux variations. As the measured flux uncertainties in the most energetic band (100-200 keV) have appeared too large

\(^{1}\) Here and below time is expressed in INTEGRAL Julian days (IJD = MJD - 51544).
for a reasonable analysis, it has been limited to the two less energetic bands (20-50 keV and 50-100 keV).

The conducted analysis consisted of two main operations: exposure filtering and rebinning. First, individual exposures with flux uncertainties larger than $|\Delta F_i| = 1.25\ \text{cnt}\ \text{s}^{-1}$ were filtered out; thus 32 20-50 keV exposures and 22 50-100 keV exposure were excluded. Next, four rebinning times scales – namely, 10, 30, 100 and 300 days – were probed. For each of the time scales we rebinned the lightcurves in each of the two analysed energy bands and checked the normality of the uncertainty distribution with the Shapiro-Wilk test [12], which has shown that in most of the bins such distribution is indeed close to normal. In order to suppress fluctuations, an additional threshold was applied to the rebinned lightcurves, namely, the bins where the number of individual exposure was below the threshold were filtered out. We found that reasonable threshold values here were between 4 and 10. The lightcurves resulted from the said filtering and rebinning are shown in Figures 2 and 3.

4. Conclusions

Although the hard X-ray lightcurves of Vela PWN show some hints of variability (see Figures 2 and 3), the performed analysis did not allow us to reveal significant flux variations in either of the considered energy bands on either of the considered time scales. This can be due either to the insufficient sensitivity of ISGRI at the relevant flux levels, or to a true stability of the flux. As the estimates of the magnetic field strength in the nebula are not very certain, it is possible that the putative flux variability could be most prominent not in the investigated hard X-ray band, but in the gamma-ray range of 1-30 MeV, where no sensitive telescope are available as of yet. Hence, a search for MeV range variability of Vela PWN and similar objects would be one of the tasks for such future gamma-ray detectors as eASTROGAM [13] or HERMES [14].
Figure 2. The 20-50 keV lightcurves of the Vela PWN shown for various values of time binning and thresholds. Time is expressed in INTEGRAL Julian days (IJD = MJD - 51544).
Figure 3. The 50-100 keV lightcurves of the Vela PWN shown for various values of time binning and thresholds. Time is expressed in INTEGRAL Julian days (IJD = MJD - 51544).
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