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The clumpy wind of Vela X-1

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Abstract

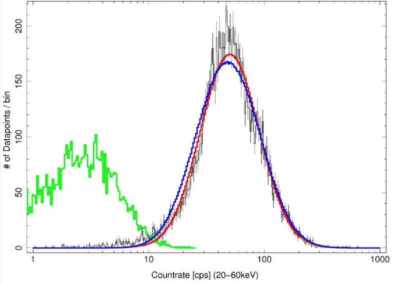
The structure of the stellar wind in the HMXB Vela X-1, consisting of a neutron star and the high mass donor star HD 77581, is investigated by analyzing the flaring behavior in X-rays.
To this end we analyzed all archival *INTEGRAL* data, calculating the brightness distribution in the 20-60 keV band. We show that the emerging distribution is closely following a log-normal distribution.
Orbital resolved analysis shows that the structure in the accretion region is strongly variable, explainable by shocks and an accretion wake. Analysis of *RXTE* ASM data shows a strong orbital change of N_{H}. Derived accreted clump masses from the *INTEGRAL* data are of the order of 10^{20}–10^{21} g.
We show that the lightcurve can be described using a model of multiplicative random numbers.
In course of the simulation we calculate the Power Spectral Density of the system in the 20-100 keV energy band and show that it follows a red-noise power law.
We conclude that a mixture of a clumpy wind and shocks and turbulences can explain the measured distribution.

The Vela X-1 system

Vela X-1 is a bright, eclipsing high mass X-ray binary (HXMB) showing strong pulsation with a pulse period of around 283 sec (McClintock et al., 1976) and an orbital period of 8.9 days (van Kerkwijk et al., 1995). The neutron star is deeply embedded in the strong stellar wind of the optical companion HD 77581 (Quaintrell et al., 2003).
The average X-ray flux is $\sim 10^{36}\,\mathrm{erg\,sec^{-1}}$, but this flux is very variable on all timescales (Staubert et al., 2004).
Giant flares up to 7 Crab have been measured, as well as off-states in which the source is not detected though out of eclipse (Kreykenbohm et al., 2008). The physical processes leading to such a strong variation are, however, not clear.

Our study addresses the question whether the giant flares are understandable as extreme values of usual flares or if other physical processes need to be invoked and we investigate the structure of the accreted mass.

Phase averaged analysis

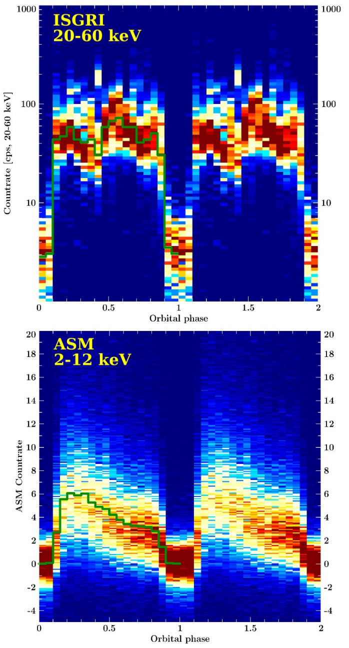


Lightcurves from *INTEGRAL*/ISGRI in the 20-60 keV band, extracted with `ii_light` (OSA 7.0) with a time resolution of 283.5 sec were analyzed.
After eliminating all data from eclipses we binned the lightcurve into a logarithmic count rate grid, between 1 and 1000 cps.
The emerging distribution is shown in the *plot above* and clearly follows a log-normal distribution. The best fit is shown in red in the *figure above.*
Giant flares with more than 300 cps still have a finite probability in this distribution, making them explainable by the same physical process as the ordinary flaring behavior.

The green curve in the plot shows the background distribution. As the mean background countrate is below 99.5% of the source countrate, a significant contribution to the source variability can be ruled out.

Deviations from the log-normal distribution could be due to varying accreting structures with orbital phase. Goldstein et al. (2004) for example showed that at phase $\phi = 0.5$ the absorption is drastically increased and ascribed this effect to the accretion wake.

Orbital resolved analysis

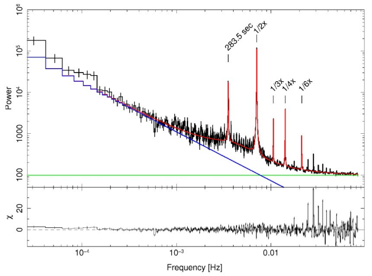


Orbital phase resolved analysis of histograms in 20 phase bins was performed.
In the plots above color indicates the probability of a datapoint of the lightcurve to fall into the respective countrate bin, i.e., the height of the histogram.
The green line shows the median of the distribution.

Top: ISGRI histograms in the 20-60 keV band. Variations are visible, but are not connected to orbital phase, but rather are statistcal in nature. Only 8 orbits were available for the analysis, allowing single outliers to dominate the overall distribution.

Bottom: ASM histograms in the 2-12 keV band. The average countrate is declining continuously over the orbit (see also Wen et al., 2006), but no short time variations are visible, as the drastically longer time span covered by the ASM data averages out instable fluctuations.
Please note that the *y*-axis is scaled linearly.
Due to the softer energy range compared to ISGRI, the ASM data are stronger affected by photo absorption.

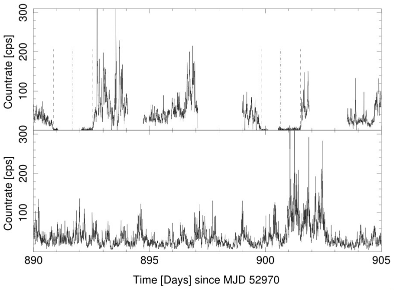
Simulation and PSD



Lightcurves showing a log-normal distribution were simulated to help us to estimate the uncertainties in the distributions and to separate the influence of the sampling from intrinsic source behavior.
They were simulated using the method proposed by Uttley et al. (2005), which makes use of the fact that a multiplication of random numbers will be log-normally distributed.

An important input parameter to the simulation is the shape of the periodogram (PSD) of the source, shown in the *plot above*. The PSD was evaluated on a lightcurve in the 20-100 keV band with 6 sec time resolution. The pulse period of 283.5 sec and its harmonics are clearly seen. The overall shape of the PSD is dominated by a powerlaw $\nu^{-\gamma}$ with γ=1.18.

An example of the simulated lightcurves is shown in the *bottom panel* of the *plot below*. The *top panel* shows a measured lightcurve, with the dashed lines indicating the eclipses. Simulation and data are very similar. The distribution gained from the simulation is plotted in the *histogram to the far left* in blue.



Results and Outlook

We have shown that:

- the brightness distribution of Vela X-1 follows a log-normal distribution.
- significant variations in the distribution at different orbital phases are visible.
- the distribution can be simulated with a simple model.

To first order the shape of the histograms is determined by the distribution of the accreted mass, neglecting any absorption and scattering effects.With an accretion efficiency of $\eta = 0.1$ the average mass accretion rate was calculated to be $\sim 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$. Assuming a flaring time of 2.5ksec this would mean that a single accreted mass clump has a mass of $\sim 10^{20}$ g. Large clumps could reach up to some 10^{21} g. These different masses could due to a clumpy wind, a model recently applied successfully to many HMXB (Dessart & Owocki, 2003, for Vela X-1 see Schulz et al., 2002).

The calculated clump sizes are in accordance with the ones presented by Walter & Zurita-Heras (2007) for a supergiant fast X-ray transients, who also assumed a clumpy wind.

The emerging log-normal distribution could be due to down grinding of larger size structures (e.g. clumps), as the grinding process can be understood as a multiplication of random numbers. As Kevlahan & Pudritz (2009) have shown for the ISM, shocks can provide a means to alter density distributions to be log-normal.

We expect that other wind accreting systems show the same kind of distributions as Vela X-1. A quick look at data from 4U 1909+075 (X 1908+07, Wen et al., 2000) confirmed the expectation for this system. A better data base in the hard X-rays is needed for all systems, which could be provided by *Fermi* GBM data.

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