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Vela X-1 as a laboratory for accretion in high-mass X-ray binaries

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Abstract. Vela X-1 is an eclipsing high mass X-ray binary (HMXB) consisting of a 283s accreting X-ray pulsar in a close orbit of 8.964 days around the B0.5Ib supergiant HD77581 at a distance of just 2.4 kpc. The system is considered a prototype of wind-accreting HMXB and it has been used as a baseline in different theoretical or modelling studies.
We discuss the observational properties of the system and the use of the observational data as laboratory to test recent developments in modelling the accretion process in High-Mass X-ray Binaries (e.g., Sander et al. 2018; El Mellah et al. 2018), which range from detailed descriptions of the wind acceleration to modelling of the structure of the flow of matter close to the neutron star and its variations.

Key words. accretion, accretion disks - stars: neutron - stars: winds - X-rays: binaries - X-rays: individual Vela X-1

1. Introduction

Vela X-1 belongs to the earliest and best known X-ray binaries in the Galaxy. It was discovered by Chodil et al. (1967) in sounding rocket flights undertaken in July and September 1966. Forman et al. (1973) identified previously found brightness variations (Ulmer et al. 1972) as caused by eclipses. Rappaport & McClintock (1975) detected that the X-ray emission was pulsed. In the following decades, up to the present, Vela X-1 has

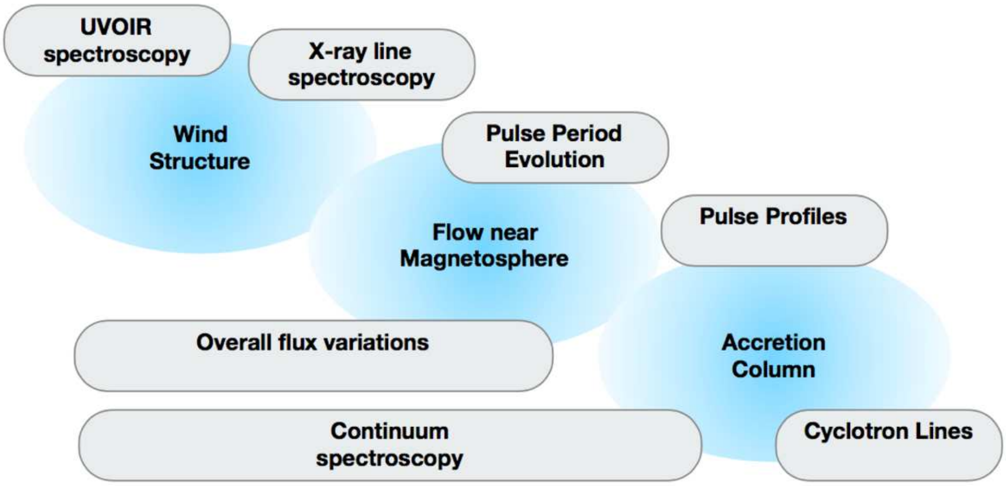

Fig. 1. Different diagnostics relate to different elements of the system.

been observed by every major X-ray instrument. Table 1 summarises the system parameters. Compared to most other X-ray binaries, the essential parameters are very well known in Vela X-1. This allows to compare modelling efforts in greater detail with the data.

Understanding an accreting X-ray pulsar system in detail requires studies at many different length scales. For Vela X-1 this ranges from the 10's of millions of km of the binary separation down to less than a km for the accretion column producing the X-rays. Different diagnostics across multiple wavelengths probe different elements and distance scales.

2. Stellar wind

One of the fundamental parameters to describe a HMXB is the velocity v of the strong stellar wind. Assuming basic Bondi-Hoyle accretion, the accretion rate scales with v^{-3} (Oskinova et al. 2012, and references therein). As Table 2 shows, different authors have over the years derived very different terminal wind speeds v_∞f, sometimes even based on the same data, but using different assumptions and approaches. In order to estimate the wind velocity close to the neutron star from v_∞f, usually a "β–law" is assumed where $V(r) = v_\infty f\,(1 - R_\star/r)^\beta$.

Using a hydrodynamically consistent atmosphere model describing the wind stratification and including effects of X-ray illumination, Sander et al. (2018) found that the velocity curve close to the mass donor may deviate significantly from a β–law, and in consequence the wind speed at the neutron star may be much lower than previously assumed. This, in turn, may lead to a very different flow of matter around the neutron star as El Mellah et al. discuss in these proceedings. Vela X-1 belongs to the earliest and best known X-ray binaries in the Galaxy. It was discovered by Chodil et al. (1967) in sounding rocket flights undertaken in July and September 1966. Forman et al. (1973)

Table 1. Vela X-1 system parameters

Distance	2.42 (2.25-2.60) kpc	Bailer-Jones et al. (2018)
Orbital period	8.964357 ± 0.000029 d	Kreykenbohm et al. (2008)
Eccentricity	0.0898 ± 0.0012	Bildsten et al. (1997)
Inclination	$i > 79$ deg	Giménez-García et al. (2016)
$a \sin i$	113.89 lt-sec	Bildsten et al. (1997)
Donor star type	B0.5Ia	Giménez-García et al. (2016)
Donor star mass	$21.5 \pm 4\ M_\odot$	Giménez-García et al. (2016)
Neutron star mass	$1.9^{+0.7}_{-0.5}\ M_\odot$	Giménez-García et al. (2016)
Neutron star magnetic field	2.6×10^{12} G	Staubert et al. (2019)
Pulse period	~283 s (variable)	Kreykenbohm et al. (2008)

Table 2. Terminal wind velocity and stellar mass loss in the Vela X-1 system, as derived by different authors with different approaches – see the references for details.

Data from	Velocity v_∞f	Mass loss rate	Reference
IUE	1700 km/s	$\sim 10^{-6} M_\odot$/yr	Dupree et al. (1980)
IUE	1100 km/s	—	Prinja et al. (1990)
IUE	600 km/s	$\sim 10^{-6} M_\odot$/yr	van Loon et al. (2001)
Chandra HETGS	1100 km/s [1]	$(1.5 - 2) \times 10^{-6} M_\odot$/yr	Watanabe et al. (2006)
IUE & ESO FEROS	700^{+200}_{-100} km/s	$10^{-6.2\pm0.2} M_\odot$/yr	Giménez-García et al. (2016)
(Same data as above)	$\sim$ 600 km/s	$10^{(-6.07\ldots-6.19)} M_\odot$/yr	Sander et al. (2018)

[1] used value from Prinja et al. (1990)

identified previously found brightness variations (Ulmer et al. 1972) as caused by eclipses. Rappaport & McClintock (1975) detected that the X-ray emission was pulsed. In the following decades, up to the present, Vela X-1 has been observed by every major X-ray instrument. Table 1 summarises the system parameters. Compared to most other X-ray binaries, the essential parameters are very well known in Vela X-1. This allows to compare modelling efforts in greater detail with the data.

3. Flux variations and absorption

While being a persistent source, Vela X-1 shows erratic flux variations on a wide variety of timescales from days to minutes. If one takes X-ray monitor data from several orbital cycles and folds with the orbital period, one arrives at a very stable *mean* profile: the observed X-ray flux peaks around orbital phase 0.2 after the eclipse egress and then a gradual falls off towards late orbital phases (Fürst et al. 2010; Falanga et al. 2015). This overall effect is energy-dependent and mainly reflects the *mean* absorption in the dense material present in the system, especially in the accretion and photoionization wakes (Grinberg et al. 2017, and references therein). Still, the lightcurves of individual orbits may look very different especially between orbital phase 0.3 and 0.6 very different absorption measures have been determined at different times. As one example, for phase 0.5, with the neutron star between HD77581 and the observer, Haberl & White (1990) found absorption columns of a few times 10^{23}, while Nagase et al. (1986) in another set of observations found an order of magnitude less.

At shorter time scales, flares with durations of hours down to individual pulses have been reported by a variety of different authors. In other cases short “off-states” with fluxes below detection limits have been observed, see, e.g., Kreykenbohm et al. (2008) for examples of both extremes. Fürst et al. (2010) found that the pulse-averaged flux in hard X-rays can be very well described by a log-normal distri-

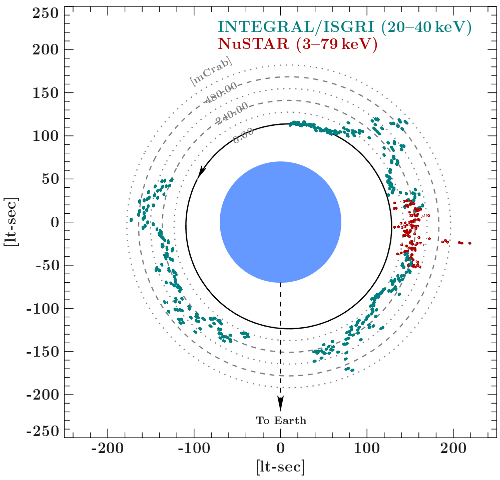

Fig. 2. INTEGRAL and NuSTAR count rates plotted over the shape of the neutron star's orbit for the observing campaign in January 2019, covering most of the binary orbit. The longer data gaps in the INTEGRAL data are due to perigee passages of the satellite.

bution. The short-term flux variations will be driven by a complex interplay between density variations in the clumpy wind and accretion physics at the magnetosphere (Martínez-Núñez et al. 2017), but the relative importance of different factors remains a point of debate.

Comparing these flux variations with models of clumpy winds can be tricky. A straightforward combination of 1D wind models and Bondi-Hoyle accretion leads to much larger predicted variations than observed (Oskinova et al. 2012). Ducci et al. (2009) simulated a range of clump sizes to obtain a good match, but require unrealistic large clump sizes. But modelling absorption just by gas clumps with clump sizes based on current stellar wind models *under-predicts* the observed absorption variations (Grinberg et al. 2017).

Further information about structures in the wind, velocities and chemical composition can in principle be gained from the study of X-ray fluorescence lines. For examples see, e.g., Sato et al. (1986), Watanabe et al. (2006), or Grinberg et al. (2017).

In a recent, relatively surprising development, Vela X-1 has now also been detected significantly at $\sim$100 μJ by the Australia Telescope Compact Array with a flat radio spectrum (Van den Eijnden et al., in prep). The analysis of these data is still ongoing, but may yield information on the structure of the accretion flow close to the neutron star.

Broadband spectroscopy and analysis of the pulse profile yield information about the "last mile", the matter in the accretion column close to the neutron star. Vela X-1 shows the typical X-ray spectrum for an accreting X-ray pulsar with an absorbed powerlaw turning over at high energies, plus an iron fluorescence line. In addition, there are two cyclotron resonance scattering features (CRSF) at $\sim$ 25 and $\sim$ 55 keV of varying relative strength (Fürst et al. 2014). The CRSF centroid energies are mildly positively correlated with flux (Fürst et al. 2014), indicating accretion in the sub-critical regime. Swift-BAT data indicate found a long-term decrease in the centroid of the harmonic cyclotron line until about 2012 (La Parola et al. 2016; Ji et al. 2019); the physics behind this are not understood.

The pulse profile of Vela X-1 is complex with up to 5 peaks at lower energies and two asymmetric peaks in the hard X-rays (Raubenheimer 1990). The general shape is largely stable against flux variations, but Doroshenko et al. (2011) found a changed pulse pattern during an "off-state". Determining the emission geometry from these patterns is a complex task, including a full general relativity treatment. While earlier attempts have been undertaken in the past (e.g., Bulik et al. 1995), no recent decomposition has been done.

4. Outlook to the future

Despite an enormous amount of published information, many details of the Vela X-1 system are still to be determined. We are working on various angles, e.g.: further deep studies of X-ray fluorescence lines; a deeper understanding of the accretion flow close to the neutron star; more realistic accretion column emission models; and multiwavelength studies including optical and radio. A recent deep observing campaign, see Fig. 2, awaits to be analysed further in the near future.

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