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THE SATELLITE SMILE – ITS PROSPECTS FOR OBSERVING COSMIC SOURCES

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Abstract. We describe the scientific potential of a Soft X-ray Imager (SXI) onboard the ESA–CAS satellite *SMILE* to study the activity of cosmic X-ray sources in the soft X-ray region and located in the fields planned to be observed by SXI. We used the 2–3 keV band flux of the monitor MAXI/*ISS*, covering at least part of the expected band of the SXI/*SMILE* telescope. We discuss how SXI can contribute to this branch and how combining the SXI/*SMILE* data with those obtained by other satellites on the same days can be helpful if the light curves of the 1-day means are used. We show these possibilities on several examples of cosmic X-ray sources (Vela X-1 and GRO J1008-57 containing neutron stars accreting matter from their companions) in the field of view of SXI. Including observations from MAXI/*ISS* and BAT/*Swift* will enable extending the coverage to the energy of 50 keV.

Keywords: Astronomical instrumentation, methods and techniques, observational methods, X-ray binaries, radiation mechanisms.

1. Introduction

The long-term X-ray activity of cosmic objects can be observed even by instruments that were designed for quite a different purpose. The ESA–CAS *SMILE* mission will investigate the response of the Earth's magnetosphere to the impact of solar wind [1, 2]. The Soft X-ray Imager (SXI) monitor onboard *SMILE* is a Lobster-eye telescope with a field of view of about 26.5 × 15.5 degrees [3]. It will observe in approximately the 0.15–3.0 keV band. Many cosmic X-ray sources of various types will be in SXI's field of view.

2. X-ray observations of cosmic sources

Inspection of X-ray spectra and luminosities (e.g. [4]) shows that X-ray binaries containing a neutron star (NS) or a black hole accreting matter from its companion radiate over a broad range of energies. To compare the light curves of these cosmic objects, we selected and used the 2–3 keV band flux I_{M} (measured in photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) obtained by the monitor MAXI onboard the *ISS* [5]. The integration time of one MAXI scan was approximately 60 seconds and the separation between these scans was 92 minutes (one orbital epoch). Its energy range of 2–20 keV can be divided into several bands by the investigator to analyze a given object later on the Earth. The 2–3 keV band partly coincides with the hardest part of the band of the planned SXI/*SMILE* experiment.

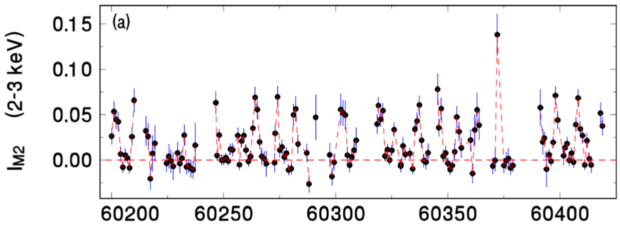
More information is given in our previous paper [6]. Here, we show how combining the SXI/*SMILE* data [7, 8] with those obtained by another satellite on the same days can extend the observed energy band, providing more information. The observations of the monitor BAT onboard the NASA satellite *Swift* [9, 10] can be used for these purposes.

BAT scans the sky as it searches for gamma-ray bursts. Beside these bursts, it also detects other types of X-ray sources. We used the measurements of the flux I_{BAT} of X-ray binaries in the 15–50 keV band [9–11]. This webpage gives fluxes of observed objects in this energy band. The BAT accumulates detector plane maps every five minutes. It is automatically used to determine the positions and fluxes of cosmic sources [12]. We used the provided one-day means of I_{BAT} and their errors. The measurements of the BAT flux I_{BAT} in the 15–50 keV band are given on [11]. Several observations of a given object were obtained per day and grouped into 1-day means. New measurements are added regularly (usually daily).

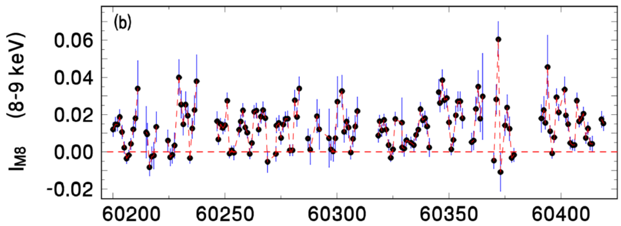
It is true that MAXI and BAT do not observe a given object at precisely the same time. Therefore, we used the 1-day means of the data from both MAXI and BAT. These averages are sufficient for the light curves of the long-term activity. Previous research has shown that analyses of combinations of the light curves of an object from various monitors are feasible and promising (e.g., [13, 14]).

The potential of astrophysics can be illustrated by the example of the following sources to be covered by SXI observations.

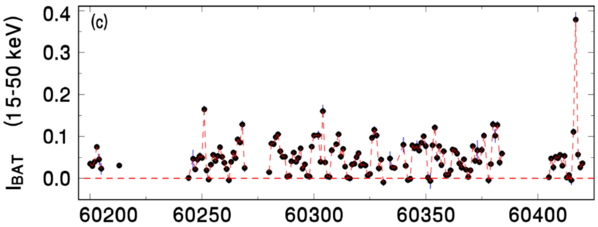
Vela X-1 contains an NS [15]. It is a high-mass X-ray binary (HMXB), its optical companion has a mass of 23.5 $M_{\odot}$, eccentricity equals to 0.0885 [16], and the orbital period P_{orb} is 8.964427 d [17]. It is



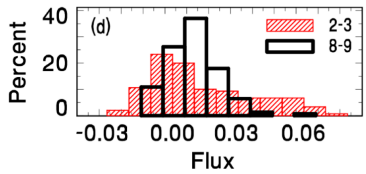
(A). A segment of the light curve of the NS X-ray binary Vela X-1 by MAXI (2–3 keV; flux in photons cm^{-2} s^{-1}; 1-day means). The densely spaced data are connected by a line to guide the eye.



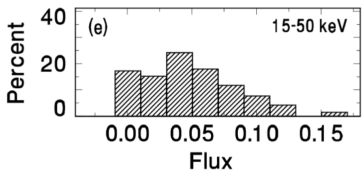
(B). The same time segment of MAXI data of Vela X-1, but the 1-day means are for energies of 8–9 keV.



(C). The BAT 15–50 keV light curve is for comparison (flux in counts s^{-1}; 1-day means).



(D). Histograms of the flux for the MAXI data in the 2–3 keV and 8–9 keV bands.



(E). Histogram of the flux from the BAT observations. The few brightest flares in the histograms fall far above the flux limits.

FIGURE 1. The long-term activity of Vela X-1 observed by various satellites in different X-ray bands.

a wind accretor; the mass-donating star may be very close to filling its Roche lobe [18].

GRO J1008-57 is an HMXB with the B0e type mass-donating star [19] and the NS [20] with $P_{\rm orb}$ of 248.9 d [21] and eccentricity of 0.68 [22]. [23] show that GRO J1008-57 undergoes both type I outbursts (the periastron passages of the NS) and type II outbursts (see [24] for an explanation of these types).

2.1. Vela X-1

Figure 1a shows a segment (about half a year) of the light curve of Vela X-1 in the MAXI 2–3 keV band (1-day means). We selected this range to approximate what can be achieved during the segmented coverage by SXI and the possible limited duration of operation of SXI and the coverage by the data. We showed in our previous paper [6] that the expected total exposure time of Vela X-1 will be several millions of seconds in the first year of SXI operations.

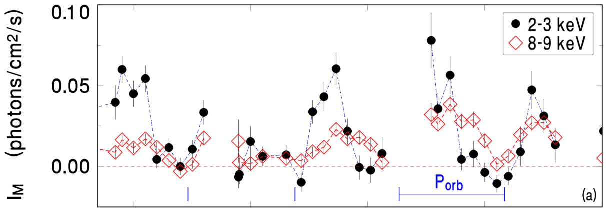
Figure 1b shows the same time segment of MAXI data, but the 1-day means are for the 8–9 keV band to approximate what we can expect from the observation in a harder X-ray band. The BAT 15–50 keV light curve is displayed in Figure 1c; these observations extend the energy band further. Meaningful comparisons of the light curves of 1-day means of X-ray fluxes of a cosmic object from various satellites will thus be possible.

The light curve of Vela X-1 consists of a long series of flares (bumps) from a base level close to $I_{\rm M}$ of zero (Figure 1). The duration of this feature is usually several days.

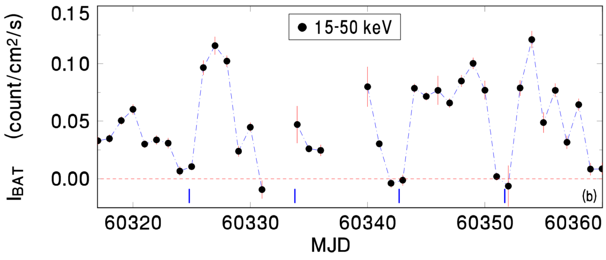
Histograms of the fluxes in the MAXI data in Figure 1 differ for the individual energies. While a histogram for the 2–3 keV flux is single-peaked with a long tail towards higher values, the 8–9 keV flux histogram is almost symmetric and considerably narrower. Although the BAT 15–50 keV quantities differ from the MAXI 8–9 keV ones, we can assess that their histograms broadly differ by asymmetry and a prominent tail of the latter.

Figure 2 compares the details of the light curves of Vela X-1 in various X-ray bands (2–3 keV, 8–9 keV, and 15–50 keV). The length of $P_{\rm orb}$ from [17] (minimum flux in MJD 48 895.2186, $P_{\rm orb} = 8.964368$ d) is displayed for comparison. Notice how the orbital modulation changes with energy, especially the difference in the branches of the minimum in MJD 60 351.7: a broad minimum in the 2–3 keV band, a considerably narrower minimum in the 8–9 keV band, and the best-defined minimum with steep branches in the hardest band (15–50 keV).

Folding the data from Figure 1 according to the ephemeris of [17] shows that although each data set shows orbital modulation, the profiles are vastly dif-

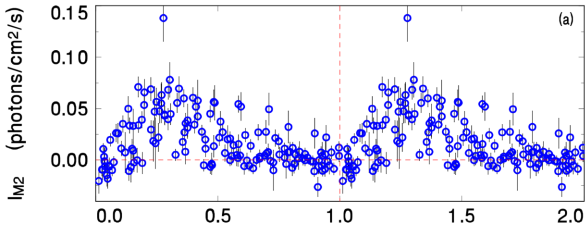


(a). MAXI 2–3 keV flux, MAXI 8–9 keV light curve.

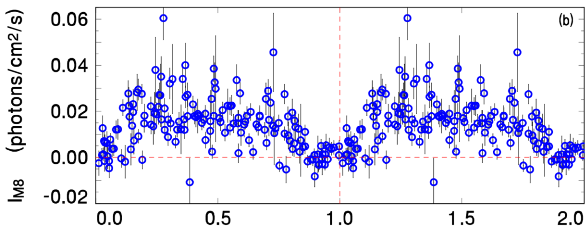


(b). BAT 15–50 keV light curve.

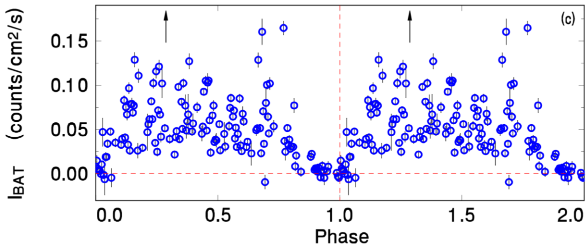
Figure 2. Comparison of the light curves of Vela X-1 in various X-ray bands. MAXI 2–3 keV flux overlaps with the edge of the SXI energy range. Compare this with the MAXI 8–9 keV light curve and the BAT 15–50 keV light curve. The ticks at the bottom of each panel denote the flux minima in the orbital modulation according to the ephemeris of [17].



(a). MAXI/*ISS* 2–3 keV overlapping with the edge of the SXI/*SMILE* energy range.



(b). MAXI 8–9 keV.



(c). BAT/*Swift* 15–50 keV.

Figure 3. Comparison of the orbital modulation of Vela X-1 in various X-ray bands from Figure 1. The ephemeris of [17] was used. Notice mainly the decreasing length of the minimum in phase 0.0 with increasing energy. The arrows denote a point with the flux beyond the scale.

ferent for the individual energy bands (Figure 3). In addition, these profiles are primarily unstable with time, as suggested by the scatter of fluxes (bigger than the error bars) in the same phase.

The orbital modulation is best visible in the 8–9 keV band, although the scatter towards higher and lower fluxes (sometimes to 0 or the instrumental limit) is visible. A narrow minimum of flux in phase 0 is visible in the 8–9 keV and 15–50 keV bands. In the 15–50 keV band, the flux rarely decreases to 0, except the well-defined primary minimum. This flux shows a large real scatter outside the primary minimum, suggesting the time evolution of this modulation.

The modulation in the 2–3 keV band, overlapping with the edge of the SXI/*SMILE* energy range, is remarkably different in phases preceding the primary minimum. The pre-minimum dip can be very long, and flux can remain close to 0 even between phases 0.55 and 1.0. A broad bump occurs between 0.05 and 0.55, but the flux can sometimes decrease to approximately 0 even here.

In summary, since the time coverage of the observation by SXI is supposed to be much longer than P_{orb} of Vela X-1, it should be possible to detect the profiles of many orbital epochs from which the orbital modulation and long-term activity consist. Figure 3 shows how the profile of this orbital modulation varies with the energy bands and how the scatter in the folded data varies with phase.

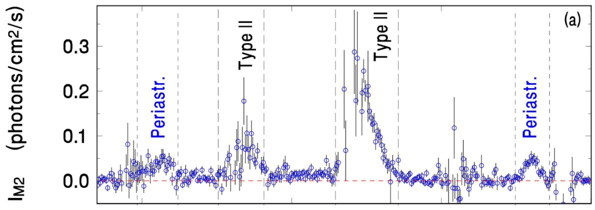
2.2. GRO J1008-57

Figure 4 compares the light curves of GRO J1008-57 in various energy bands. It is a hard X-ray source because the MAXI 2–3 keV brightenings (type I and type II outbursts) are accompanied by strong flux increases in the BAT 15–50 keV region. The periastron passages (type I outbursts) show similar durations and profiles in both bands.

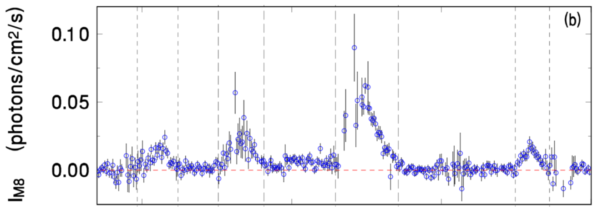
The well-determined times of the ends of the intense type II outbursts in Figure 4 show that these events finished simultaneously in the individual energy bands. The starts of the rises are less clear for the 2–3 keV band because of the increased noise.

Also, the outburst profiles are similar for these bands. Type II outbursts occurred near aphelion, which we interpret as transiting the NS through the clouds of matter far from the mass-donating star. Dimensions of these clouds must be small because the NS transits through two of them during a single orbital cycle.

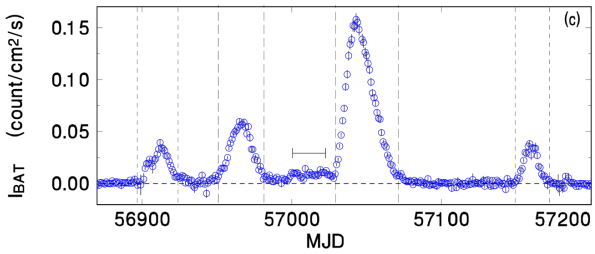
In addition, extending the energy bands to 15–50 keV through the application of BAT shows that the light curves of GRO J1008-57 indicate a detection of a hard X-ray brightening between the neighboring two type II outbursts in a single orbital epoch. The X-ray emission of this brightening is hard, as suggested by the fact that it is hidden in the observing noise in the 2–3 keV band.



(a). MAXI (2–3 keV).



(b). MAXI (8–9 keV).



(c). BAT (15–50 keV).

Figure 4. Comparison of the light curves of GRO J1008-57 in various energy bands. The dashed vertical lines represent the beginnings and ends of selected features in the light curves. A horizontal bar in panel (c) denotes a transient brightening in hard X-rays. Periastr. is periastron passage (type I outburst).

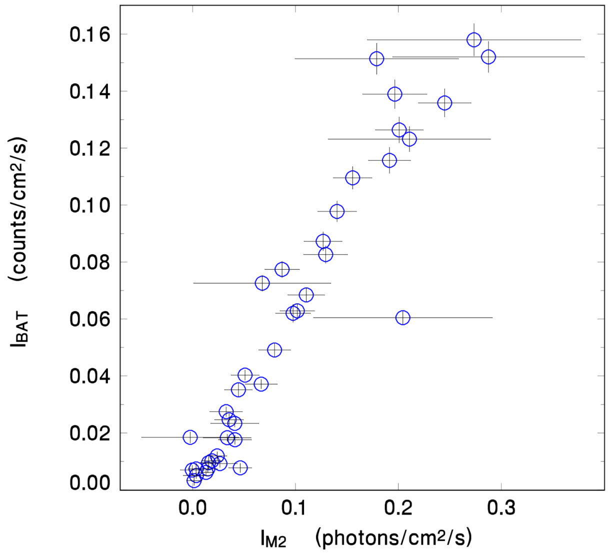


Figure 5. Correlation of I_{M2} and I_{BAT} during a broad type II outburst in GRO J1008-57. This outburst from Figure 4 peaks at about MJD 57 040.

Figure 5 shows a correlation of I_{M2} and I_{BAT} during a broad type II outburst from Figure 4. It shows that both the rising and the decaying branches are very similar to each other within the error bars. This suggests that the X-ray spectrum does not undergo significant time variations during this event.

In summary, investigations of both type I and type II outbursts in the very soft X-rays by SXI/*SMILE* can provide more information about the absorption variations in the circumstellar matter the NS transits through. Because each of these outbursts lasts for several days or weeks, it is possible to use the 1-day means in various monitors and extend the coverage to 50 keV.

3. Conclusion

We continue describing the scientific potential of a Soft X-ray Imager (SXI) onboard *SMILE* (designed for magnetospheric research) for investigating cosmic X-ray sources in soft X-ray region. We show how SXI can contribute to observing the long-term activity of X-ray binaries and how combining the SXI/*SMILE* data with those obtained by the monitors MAXI onboard the *ISS* and BAT onboard *Swift* on the same days can be helpful if the light curves consisting of the 1-day means are used. We assumed examples of two cosmic objects located in the planned fields to be observed by SXI. We analyzed the typical features of the activity that are distinguishable on the light curves with a 1-day binning of the data.

Including observations from BAT/*Swift* will extend the coverage to the energy of 50 keV. Using the still operating MAXI will allow covering the energy gap between the SXI and BAT. The 1-day means enable us to compare the light curves in various bands, such as the very strong orbital modulation in Vela X-1 and transitions of the NS through matter in the vicinity of the mass-donating star in GRO J1008-57.

Acknowledgements

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