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Development of an operation plan for observing the Galactic center region with the lobster-eye monitor

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Abstract. Using a CubeSat-like satellite, we show the lobster-eye (LE) monitor's perspectives and development of an observing plan. This instrument is important because it is able to provide wide-field X-ray imaging. We present the possibilities of monitoring the Galactic center region in the soft X-ray energy (a few keV) bands. The reason is that many X-ray binaries concentrate in the bulge surrounding the center of our Galaxy. Several such binaries are expected to be present in the monitor's field of view (typically a square of about 5×5 degrees or more) at the same time. We used the planned LE telescope's 3–6 keV and 6–9 keV band flux. To compare the expected results, we used the data obtained by MAXI/*ISS* and accommodated these energy bands to assess the object types and their light curves expected to be detected by this LE. We show how such data of GX 5–1 can contribute to this branch.

Key words: X-rays: binaries – Radiation mechanisms: general – Astronomical instrumentation – Methods: observational

1. Introduction

X-ray binaries are systems that contain a neutron star (NS) or a black hole (BH), accreting matter from their companions (donors). The donor can be either a low-mass star in a low-mass X-ray binary (LMXB) or an early-type high-mass star in a high-mass X-ray binary (HMXB). This mass accretion produces X-ray emissions that are highly variable on various timescales. Reviews of these systems can be found, e.g., in Lewin et al. (1995) and Lewin & van der Klis (2006).

X-ray monitoring enables observing various states of activity, particularly often unpredictable events of an object. It helps place these events in the framework of activities of various types of X-ray sources. This approach also enables making a representative ensemble of events in such objects.

The recent progress in CubeSat-related techniques and technologies allows missions with small scientific payloads like novel lobster-eye (LE) telescopes to be considered (Hudec et al., 2010; Tichý et al., 2015; Hudec, 2017; Hudec et al., 2018; Hudec, 2019a; Tichý et al., 2019; Hudec, 2019b; Dániel et al., 2022).

The CubeSat unit is a cube of 10 cm × 10 cm × 10 cm. These cubes can be assembled into multiples to accommodate the equipment of larger satellites. If we use the miniature LE telescope with the necessary equipment, a small resulting cubesat could consist of at least two cubes, analogously to VZLUSAT1 minisatellite (Daniel et al., 2019). Typically, one LE module provides a field-of-view (FOV) of 5×5 deg, so if one needs a larger FOV, several such modules are necessary. In addition, more units (more than four) are necessary for pointed mode because the satellite must also accommodate an altitude control system.

We note that CubeSats are able to accommodate miniature LE systems covering a reasonable FOV, as mentioned above. Although achieving remarkably large FOVs is possible by modular concept with more LE modules, we note that even a single module can provide valuable scientific results with a sophisticated observing strategy.

2. MAXI observations for comparison with LE

We already described in our previous paper (Šimon & Hudec, 2022) that we used the data obtained by MAXI/*ISS* (Matsuoka et al., 2009) to assess the light curves of various objects that are expected to be detected by simple LE monitor in X-rays with energy of a few keV. We mainly used the 3–6 keV and the 6–9 keV MAXI data. These energies are close to the expected bands of the LE telescope and its available detector.

The flux in the 1-day mean of observations is abbreviated as I_{M} in Fig. 1. We set the time of each such 1 day-bin to the beginning of each day's monitoring. The integration time of one MAXI scan was about 60 s, which comes in every 92 minutes. Therefore, the total exposure time of a given celestial object is about 15 minutes per day. We show an example of what features of the X-ray light curve can be observed with such exposure time. The light curves of all observations are available at [1] and [2].

2.1. Example of activity of GX 5–1 in the LE observing plan

Figure 1 shows an example of the activity of the LMXB GX 5–1 in the 3–6 keV and 6–9 keV bands (one-day means of data). It is a Z-source (Hasinger & van der Klis, 1989; Jackson et al., 2009). The X-ray spectral changes from flaring branch to normal branch and horizontal branch can occur for several hours.

GX 5–1 is a bright X-ray source. Besides studies of its X-ray activity, it is also helpful for the testing flight of the LE monitor. MAXI observes it in a

[1] http://maxi.riken.jp/top/lc.html

[2] http://maxi.riken.jp/mxondem/

typical I_{M} of $\sim$1.8 photons cm^{-2} s^{-1} in the 3–6 keV band. For comparison, the 3–6 keV I_{M} of Crab nebula observed by MAXI is $\sim$1.4 photons cm^{-2} s^{-1}.

Figure 1 shows that the 3–6 keV and 6–9 keV band fluxes (1-day means) of GX 5–1 significantly vary on the timescale of days. The relatively recent segment of observations, spanning about 200 days, was selected to show the current activity state. Most observations accumulate in a broad, gradually winding belt, suggesting the flux changing on various timescales detected by the 1-day means.

Figure 1 shows that the light curve of the 3–6 keV data is significantly different from that for the 6–9 keV band. A series of short drops (about weeks) of flux contributes only to the softer band.

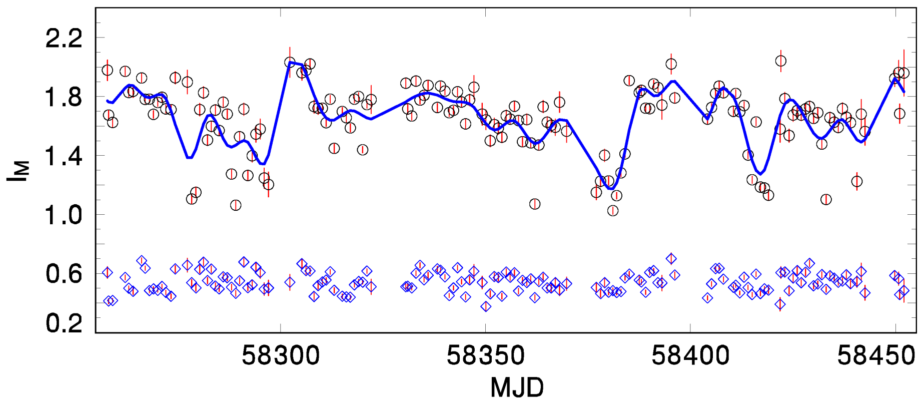

Figure 1. Example of activity of the Z-source GX 5–1 in the 3–6 keV and 6–9 keV bands. Empty circles denote the 1-day means of the MAXI 3–6 keV data. Empty diamonds represent the 6–9 keV data. Their error bars are included in the diagram; some sizes are comparable to the sizes of the symbols. The line represents a HEC13 fit with $\epsilon = 1$ and $\Delta T = 5$ d to the 3–6 keV band observations. A fit runs through a broad belt of observations with significant rapid (day-to-day) flux variations.

To separate the long-term evolution of GX 5–1 from its shorter-term activity, the light curve consisting of the 1-day means was smoothed by the code HEC13, written by Prof. P. Harmanec [3], and based on the method of Vondrák (1969). Regardless of their profile, it can fit a smooth curve to the non-equidistant data. A full description can be found in Vondrák (1969). HEC13 uses two input parameters, ϵ (in dimensionless units) and ΔT (in days in our case). We found that a HEC13 fit with $\epsilon = 1$ and ΔT=5 d represents the 1-day data running through the belt caused by the day-to-day changes (the thick line in Fig. 1). A single deviating 1-day mean with the error bar considerably lower than the amplitude

[3] http://astro.troja.mff.cuni.cz/ftp/hec/HEC13/

of this difference only slightly influences this fit. Only groups of several points are essential.

This fit shows significant flux modulations on the timescale of weeks. The fitted flux repeatedly decreases and subsequently returns to roughly the same value, thus forming a series of undulations. We show that even a 1-day binning that may be used in the testing LE is able to investigate the long-term activity of GX 5–1.

A data fitting emphasizes the light curve's features on long timescales like weeks and months. The observing noise, flares, dips, and possible features of the orbital modulation of GX 5–1 are suppressed by this fitting. Because Jackson et al. (2009) shows that the X-ray spectral changes among the branches of this Z-source can occur during several hours, they cannot cause the waves shown by the HEC13 fit in Fig. 1. Interpreting the fit to the data in Fig. 1 requires contributing another mechanism. The reason is the discrepant timescale. The shifts across the Z-branch could contribute to forming the winding belt. In principle, the fits to the light curves for the different energy bands differ.

The histograms of $I_{\rm M}$ in Fig.2 show discrepant profiles of X-ray flux for different energy bands. While the 1-day data means of the 6–9 keV band flux create a single roughly symmetric bump without remarkable wings, the 3–6 keV band $I_{\rm M}$ gives significant broad wings with a long tail toward low flux. The occasional 3–6 keV flux depressions are reflected in the tail in the histogram in Fig.2. A comparison of the histograms for the 1-day means of $I_{\rm M}$ and the fits by HEC13 shows that rapid changes like observing noise, flares, dips, and possible orbital modulation are suppressed by this fitting.

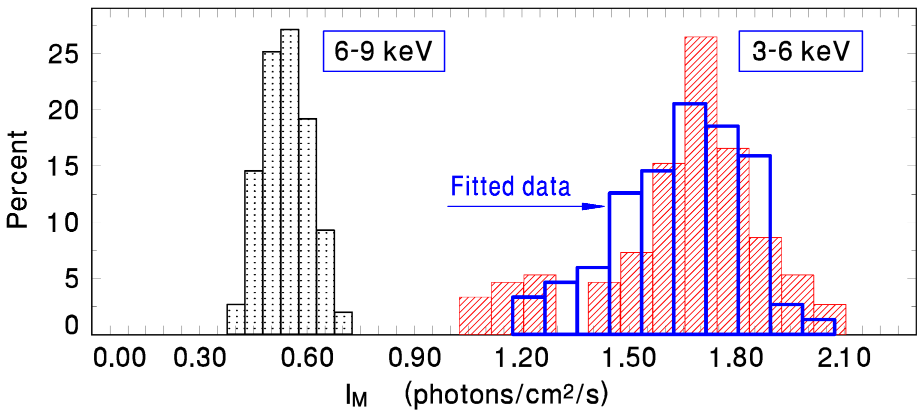

Figure 2. Histograms of $I_{\rm M}$ of GX 5–1 in the 3–6 keV and 6–9 keV bands (both for the 1-day means of the data (hatched bars) and the HEC13 fit (empty bars)).

The luminosity of GX 5–1 is close to the Eddington luminosity ($\sim$7 10^{38} erg s^{-1}

in the 1–30 keV band) (Jackson et al., 2009)), so it is reasonable to suppose that the accretion disk is always in the ionized state. Therefore, we ascribe these fluctuations of I_{M} to the variations of the mass transfer rate from the companion. Phillips & Podsiadlowski (2002) showed that the radiation pressure of strong external irradiation close to the Eddington limit causes a non-axisymmetric deformation of the donor's surface.

Furthermore, Phillips & Podsiadlowski (2002) showed that if the accretion disk shadows the inner Lagrangian point from strong external irradiation, the radiation pressure further modifies the donor's surface deformation. The transferring matter (e.g., a bulge in the impact stream region on the outer disk rim (Livio et al., 1986)) between the irradiating light source and the donor star can modify the irradiation of this star. We ascribe the undulations of I_{M} on the timescale of weeks to the effects of the pressure on the irradiated donor. The observed recurrent changes of I_{M} on the timescale of weeks can be caused by the changes in the geometric configuration of the irradiated donor with time. E.g., increasing the size of the bulge in the impact of the stream onto the disk gives rise to screening of irradiating flux; it leads to a change in the shape of the irradiated donor, hence a decrease of the mass outflow through the stream. Modeling time variations of the impact disk region and their influence on blocking the donor's irradiation is essential.

The LE dense (typically about 10 min time resolution in pointed mode) monitoring can enable tracking of the long-term I_{M} variations of GX 5–1 even when the observations are grouped into the 1-day bins. Separating into several energy bands can show a dependence of amplitude on energy. Resolution of the structure of the winding belt of I_{M} and the relation of this structure to the undulations occurring on the timescale of weeks will be essential. They will be in the possibility of an LE monitor in a CubeSat-type satellite.

3. Conclusions

We show progress in preparing the observing plan and an observational strategy of a small LE telescope in a pointed mode in a small (CubeSat-like) satellite. This telescope is able to provide wide-field X-ray imaging and monitoring. We present the possibility of monitoring the Galactic center region in the relatively soft X-ray energy band (which is constrained by the optics and the available detector).

The reason for selecting this region is that many X-ray binaries (especially those with a low-mass lobe-filling secondary and mostly the NS accretor) concentrate in the bulge surrounding the center of our Galaxy.

Several X-ray binaries are expected to be present in the monitor's FOV (a square of about 5×5 degrees). It will enable obtaining the light curves of several objects without apriori information of their state of activity. Also, early phases of outbursts of yet-unknown transients can be observed. X-ray binaries' long-term activity in this region can be reliably observed even with sufficiently long exposure times (e.g., about 1 day). Observing in the soft X-ray band is the most promising because the X-ray intensity of these objects is the highest in this band.

Such LE monitor can reliably observe the typical features of such objects' long-term X-ray activity (e.g., outbursts and state transitions). The observed data will be essential and valuable for scientific analyses.

We show that fitting the X-ray light curve with HEC13 enables us to track the profile of the long-term flux variations that may be hidden in relatively rapid (day-to-day) changes. Separating the energy band into several sub-bands wide enough to allow for the detection of cosmic objects by a CubeSat LE, at least in the case of the relatively bright objects, can enable analysis of the differences in the light curves and histograms of I_{M}.

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