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A Universal Correlation between the Duration and the X-ray Luminosity in Stellar Flares

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Since the launch in 2009 August, with the unprecedentedly high sensitivity as an all-sky X-ray monitor, MAXI has caught more than a hundred of huge flares from stars. Most of them are from low-mass, active stars (RS CVn systems, an Algol system, dMe systems, a dKe system, Young Stellar Objects). With the total radiative energy of 10^{34}–10^{39} ergs, the MAXI detections have broken the record of the largest flaring magnitudes in each stellar categories. The enlarged sample of intense flares has enabled us to do systematic studies in various viewpoints. One of the studies is the discovery of a universal correlation between the flare duration and the intrinsic X-ray luminosity, which holds for 5 and 12 orders of magnitude in the duration and L_X, respectively (Tsuboi et al. 2016). Here, we review the studies of stellar flares obtained with MAXI.

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1. Introduction

X-ray flares are observed on cool stars including the Sun. The flares are characterized with the fast-rise and slow-decay light curve. Those rapid time-variability generally follows the rise and decay in the plasma temperature. The general understanding, based on the numerous studies of solar flares, is that such features arise as a consequence of a sudden energy release and relaxation process in the reconnection of magnetic fields on/around stellar surfaces.

The study of the X-ray flares have been made with pointing observations ([9], [4], [1], [3], and references therein) and monitoring observations with X-ray all-sky monitors such as Ariel-V/SSI, GRANAT/WATCH, and Swift/BAT ([10] and [11]). Using the data of Ariel-V/SSI spanning for 5.5 years, Pye et al. (1983) and Rao et al. (1987) detected in total twenty flares from seventeen stellar sources, including ten RS CVn systems and seven dMe stars ([10], [11]). Rao et al. (1987) showed that there is a positive correlation between the bolometric luminosity and the X-ray peak luminosity.

Recently, an intensive monitoring of large flares with all-sky X-ray surveys, has been made with the Monitor of All-sky X-ray Image (MAXI; [5]). The number of the detection of the large flare was increased significantly. Tsuboi et al. (2016) found the correlation between X-ray bolometric luminosity and the duration time which holds from solar microflares to giant stellar flares detected with MAXI [15].

In this paper, we review the giant flare samples obtained with MAXI, and the derived correlation between the duration of and L_X in stellar flares. MAXI is a mission of an all-sky X-ray monitor operated in the Japanese Experiment Module (JEM; Kibo) on the International Space Station (ISS) since 2009 August. It observes an area in the sky once per 92 min orbital cycle, and enables us to search for stellar flares effectively.

2. MAXI Monitoring Observations

The MAXI monitoring observations of the stellar flares have been conducted with the GSC detector. The detector covers an energy range of 2 to 30 keV [5, 6]. The data from 2009 August 15th to 2011 August 15th are used there. All the data they used were delivered from the MAXI database system [7].

The GSC consists of twelve pieces of proportional counters, which employ resistive carbon-wire anodes to acquire one-dimensional position sensitivity. The GSC typically scans a point source on the sky during a transit of 40–150 seconds with a FoV of $1^\circ.5$-width (FWHM) every 92-minute orbital period. The transit time depends on the source incident angle in the Anode-Wire Direction. The detector area for the target changes according to the triangular transmission function of the collimator during each transit. The peak value is 4–5 cm^2 per one camera. The detailed performance of the GSC was described by [14].

3. MAXI Flare Sample

During the two-year MAXI/GSC survey, Tsuboi et al. (2016) detected twenty-three energetic flares from thirteen active stars (eight RS-CVn stars, three dMe stars, one YSO, and one Algol type star) [15]. The physical parameters of the flares are very large for stellar flares in all of the followings: the X-ray luminosity L_X (10^{31-34} ergs s^{-1} in the 2–20 keV band), the emission measure EM (10^{54-57} cm^{-3}), the e-folding time (10^{3-6} s), and the total energy released during the flare (10^{34-39} ergs).

The survey showed that the number of the flare sources with extremely large flares is very limited; only ten out of the 256 active binaries within the 100 pc distance have been detected, while four of the ten sources showed flares multiple times. The MAXI stellar sample has especially fast rotation velocities with an order of 10 km s^{-1}. This indicates that the rotation velocity is an essential parameter to generate big flares.

They detected no X-ray flares from solar-type stars, despite the fact that fifteen G-type main-sequence stars lie within 10-pc distance. This implies that the frequency of the superflares from solar-type stars, which has L_X of more than 1×10^{30} ergs s^{-1}, is very small.

On the EM–kT plot, their sample is located at the high ends in the universal correlation, which ranges over orders of magnitude ([2], [12]). According to the theory of Shibata & Yokoyama (1999) [12], the MAXI sample has the similar intensity of magnetic field to those detected on the Sun (∼15–150 G), but has orders of magnitude larger flare-loop sizes than those on the Sun (< 0.1 $R_\odot$). The largest two loop sizes from UX Ari and II Peg are huge, and might be much larger than even the binary separations.

4. A Universal Correlation between the Duration and the X-ray Luminosity

Tsuboi et al. (2016) plotted the duration vs. the intrinsic X-ray luminosity (L_{X_bol}) in the 0.1–100 keV band, using the data of solar and stellar flares in literatures and the data of the flares on MAXI/GSC sources (see Fig. 1). The plot indicates that there is a universal positive correlation between L_{X_bol} of a flare and its duration, such that a longer duration means a higher L_{X_bol}. The correlation holds for the wide range of parameter values; 12 and 5 orders of magnitude in L_{X_bol} and duration, respectively. The MAXI sample is located at the highest ends on the correlation. From the data, they found that the duration is proportional to $L_{X\_bol}^{0.2}$.

The positive correlation between the flare duration and the X-ray luminosity can be described with the cooling model of a single flare. The cooling can be modeled by either a radiative or conductive process. More luminous flare has higher temperature, as we see in the EM–kT diagram (see above section). In the radiative cooling model, simply, the higher temperature makes the cooling time longer. In the conductive cooling model, it is expected that the more luminous flare accompanies with the longer flare loop. The longer flare loop makes the conductive cooling timescale longer.

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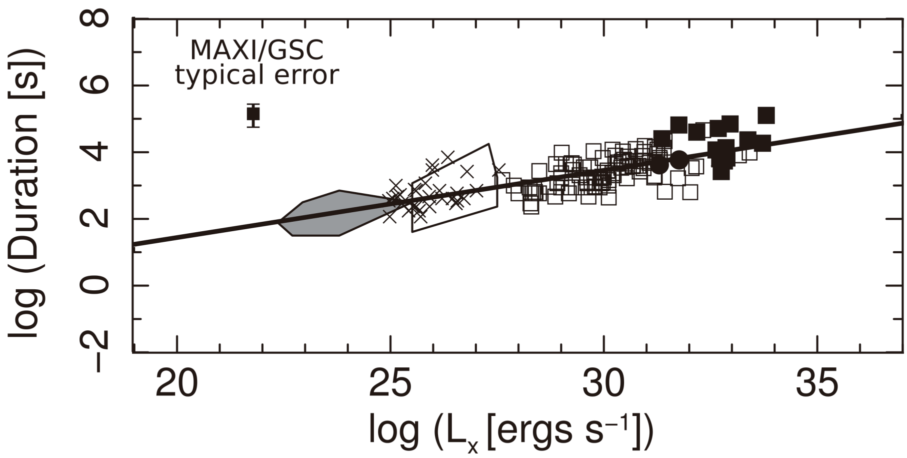

Figure 1: Log-log plot of the duration of flares vs. X-ray luminosity in the 0.1–100 keV band (from Fig. 5 in Tsuboi et al. 2016). The best-fit model is inserted with a broad solid line. The filled squares, filled diamond, filled circles and filled triangle show RS-CVn type stars, Algol, dMe stars and TWA-7, respectively. Stellar flares from RS-CVn type, Algol, dMe stars and YSOs in literatures are indicated with open squares. Three sets of data for solar flares are also superposed: X marks, large open pentagon and large gray region, taken from [8], [16] and [13], respectively.

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