PROCEEDINGS OF SCIENCE

X-ray Emission from Stars ∼The Results Obtained with MAXI∼

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The Japanese astrophysical payload MAXI (Monitor of All-sky X-ray Image) has been monitoring the variable X-ray sky since August 15, 2009 from the International Space Station. With the 10 year's unbiased survey, the nature of the largest stellar flares and the hosts have been gradually revealed. We recognized that the flares, which MAXI detected, are occurred from limited number of active stars repeatedly, and most, so called "active stars" are quiet in MAXI's monitoring. It is notable that the most energetic flare source in the MAXI sample is the quadruple system GT Mus, which is located at 109.594 pc distance (Sasaki et al. 2020). We will review the MAXI monitoring of GT Mus. We also introduce the follow-up observation with NICER.

Multifrequency Behaviour of High Energy Cosmic Sources - XIII - MULTIF2019
3-8 June 2019
Palermo, Italy

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PoS(MULTIF2019)054

1. Introduction

Stellar flares are thought to be a resultant of magnetic reconnection on a stellar surface. The process can be watched in X-ray movies of the Sun; in the movies, X-rays are emitted in plasma loops, which trace the shape of magnetic fields, and with an abrupt ignition, plasma starts to fill the loops. As for the flares on the stars other than the Sun, the same process is inferred from mainly the time variation of physical parameters. For example, we see the fast-rise and slow-decay in light curve of stellar flares, or we see the flare temperature peaks before the Emission Measure (*EM*) does, i.e., harder emission peaks before softer emission, all of which are seen in the solar flares as well. However, despite of the analogy, the geometries of the reconnected magnetic loops are not fully understood in the case of large flares, especially. For example, one proposed that the loops are connected between binary components, and the other one assumed that they are connected between the star and the circumstellar disk.

In order to investigate the origin of the giant flares, we have been monitoring stars in the X-ray band with the Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009 [1]). 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. Here, we report the results with the gas proportional counters (GSC) of MAXI obtained in the first 10-year operation from 2009 August.

2. Results

2.1 Detected Flares and the Source Categories

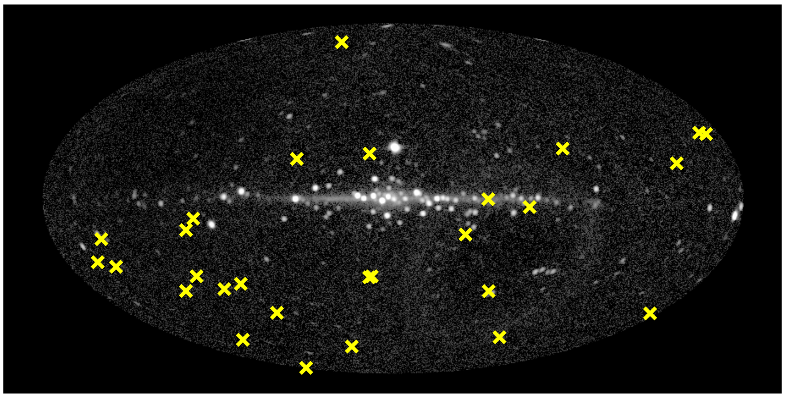

Figure 1: The location of flare stars detected with MAXI/GSC, overlaid on MAXI all-sky map

MAXI detected more than one-hundred flares on twenty-eight low-mass stars; fourteen RS CVn systems, one Algol system (Algol), ten dMe stars, one dKe star, one Young Stellar Object (TWA-7) and one K-type variable star. The detection of the flare from TWA-7 and the results from the first two-year monitoring with MAXI have been already reported in Uzawa et al. (2011) [2] and Tsuboi et al. (2016) [3], respectively. Most of the categories are classified as active binaries, which consist of the pair of a sub-giant and a main sequence, a pair of a giants and main-sequence, and a pair of two main-sequence stars. The distance between each stellar component are 1–2 times of their own stellar sizes.

Figure 1 shows the flare stars detected with MAXI/GSC overlaid on MAXI all-sky map. The widely dispersed source distribution indicates that the flare sources detected with MAXI are closely located from us. The assumption is validated with Figure 2, which shows that the MAXI sources are within about 200 pc, and the detection limit of MAXI/GSC is roughly 10 mCrab. The observed parameters of all of these MAXI/GSC flares are found to be at the upper ends for stellar flares with the luminosity of 10^{31-34} ergs s^{-1} in the 2–20 keV band, the emission measure of 10^{54-57} cm^{-3}, the *e*-folding time of 1 hour to 1.5 days, and the total radiative energy released during the flare of 10^{34-39} ergs (see Figure 3). Tsuboi et al. (2016) [3] found a universal correlation between the flare duration and peak X-ray luminosity, combining the X-ray flare data of nearby stars and the Sun. Moreover, they found that the data-points of the MAXI-detected flares lie on the extension of the established correlation between the flare-peak emission measure and temperature for solar flares and small stellar flares [4]. These correlations hold over a broad range of energies, from solar micro flares to large stellar flares. It suggests some common mechanism working in flare-triggering and cooling processes.

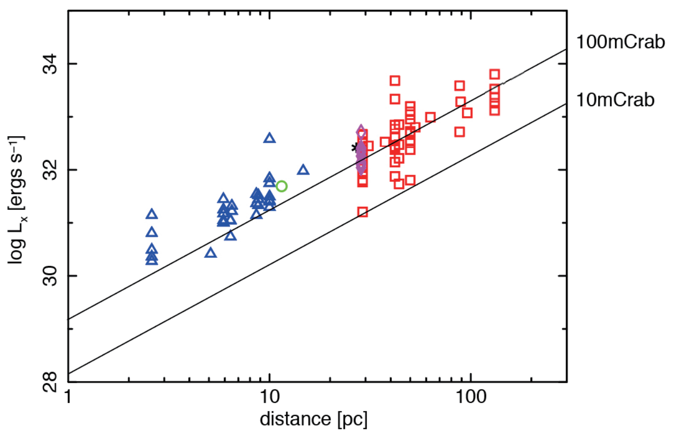

Figure 2: Log-log plot of X-ray luminosity in the 2–20 keV band of flares vs. distance from stars detected with MAXI/GSC. The squares, triangles, circle, diamond, and star show RS-CVn type stars, dMe stars, dKe star, Algol, and TWA-7, respectively. The detection limit appears to be roughly 10 mCrab in the 2–20 keV band.

The detected sample of active binaries is only the tip of the iceberg; within 100 pc distance, 256 active binaries are known to exist, but only 1/10 are detected. Four of them (UX Ari, HR1099, AR Lac and II Peg) exhibited flares more than twice. It is notable that none of the solar type stars has been detected, despite that within 20 pc distances, there are 15 such stars.

Although most of the flare sources detected with MAXI/GSC are multiple-star system, two of them were single stars: TWA-7 and YZ CMi. In addition, another two (AT Mic and EQ Peg) have, though a binary system, a very wide binary-separation of roughly 6000 solar radius, and so are the same as single stars practically. All of these four stars are known to have no accretion disk. These results reinforce the scenario that neither binarity nor accretion, nor star-disk interaction is essential to generate large flares, as has been already discussed in Uzawa et al. (2011) [2] and Tsuboi et al. (2016) [3].

2.2 The Most Energetic Flare Source, GT Mus

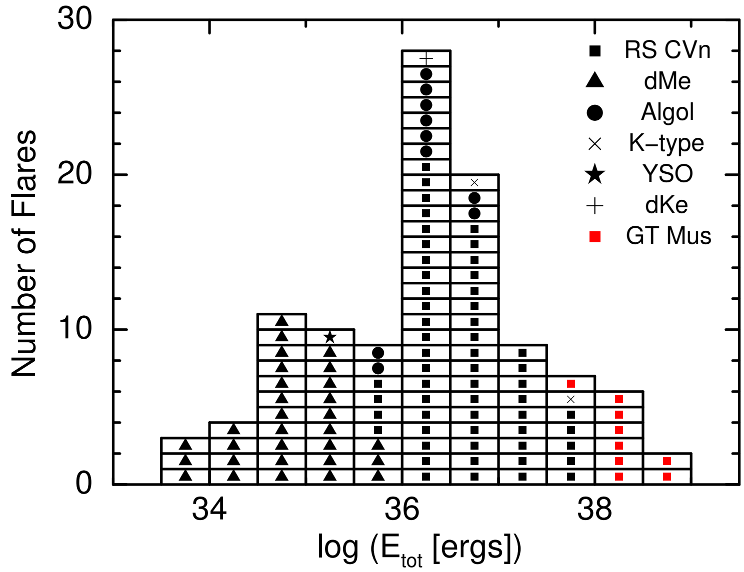

Figure 3: Distribution of the radiative energy during a flare in the 2–20 keV band.

From Figure 3, it is found that the flares with the total energies over 10^{38} erg were all detected from one source, GT Mus.

GT Mus (HR4492) is a quadruple system comprised of two binary systems named HD101379 and HD101380 at a distance of 109.594 pc [6], [7]. These two binaries are spatially resolved by speckle methods with the separation of 0.23 arcsec [5]. The primary of the HD101379 is thought to be the chromospherically dominant source among the quadruple components, with strong emission lines in the optical band and large amplitude of rotational modulation in the photometric light curve. The primary is a giant with spectral type of a G5/8 with the radius of $16.56R_{\odot}$ [6], [7]. The periodicity seen in the light curve, 61.4 days, is notably long, though HD101379 is classified with RS CVn system, which are close binaries with tidal locking and then generally associated with quick rotation.

During 10-year period, GT Mus showed extremely large, recurrent, flares. One should remind of the 11-years sunspot cycle at the Sun. On the Sun, its X-class flares tend to occur in the period near the solar maximum, spanning about a half of a solar cycle ($\sim$5.5 years) [8]. Analogously, GT Mus might have long-term activity cycle of about 20 years. The activity cycles of other RS CVn-type stars have been reported in the past, including a spot cycle of 14–20 years for HR1099 (V711 Tau) [9, 10, 11], 9.2 years from II Peg [12], and 15 years from LQ Hya [13]. Although the spot cycle of GT Mus is unknown, the activity cycle of 20 years is consistent with those of other RS CVn-type stars. Future monitoring observations will determine how long the active phase of GT Mus lasts.

The primary of the HD101379 is known to have the mass of $M_* = 2.7M_\odot$ [14], which is in the range of intermediate mass stars ($1.5M_\odot < M_* < 3.8M_\odot$). Since there has been less studies for magnetic activities in intermediate mass stars, Sasaki et al. (2020) [15] evaluated the activity of GT Mus using the X-ray to bolometric luminosity ratio (L_X/L_{bol}) versus the Rossby number (R_o) diagram, where good correlation is established in low-mass main-sequence stars. Here, the Rossby number (R_o) is a ratio of the rotation period to the turnover convective timescale [16]. As the result, GT Mus was plotted on the same trend with the established correlation. Sasaki et al. (2020) also plotted the other giant binaries in the same diagram, and confirmed that the sources distribute on the same trend again, but are located at the lower location than GT Mus. This suggests that GT Mus is at a high magnetic activity level, consistent with what is inferred from its recurring large flares.

2.3 Followup Observation of a Stellar Flare on GT Mus with NICER

A three-day follow-up X-ray observation of GT Mus was performed with NICER from 2017 July 18, 1.5 days after the MAXI detection of the flare from GT Mus. NICER is a non-imaging X-ray detector installed on the ISS in 2017 June. NICER has the X-ray Timing Instrument [17] composed of 56 co-aligned X-ray concentrator optics (XRCs) and silicon-drift detectors (SDDs). Each XRC collects X-ray photons over a large geometric area from a 15 arcmin^2 area of sky. The XRCs focus photons onto the SDDs. The SDDs have a sensitivity in 0.2–12.0 keV with an energy resolution of 85 eV at 1 keV. The XTIs provide a large effective area of $\sim$1900 cm^2 at 1.5 keV. In practice, out of 56 XRCs, 52 XRCs are operated in orbit.

The time-resolved spectra obtained with NICER suggest that the flare of GT Mus was cooling quasi-statically during the NICER observation period. Based on the quasi-static cooling model [18], the flare loop length is estimated to be $5.1\pm0.4 \times 10^{12}$ cm ($73\pm6\ R_\odot$). This is by two orders of magnitude larger than that of the typical solar flare loop of 10^9–10^{10} cm. This is corresponding to four times of the stellar radius of GT Mus, on the other hand.

3. Summary

1. Since August 15, 2009, MAXI has been monitoring the variable X-ray sky from the International Space Station. With the 10 year's unbiased survey, more than one-hundred flares were detected from twenty-eight low-mass stars; fourteen RS CVn systems, one Algol system (Algol), ten dMe stars, one dKe star, one Young Stellar Object (TWA-7) and one K-type variable star.

2. The observed parameters of all of these MAXI/GSC flares are found to be at the upper ends for stellar flares with the luminosity of 10^{31-34} ergs s^{-1} in the 2–20 keV band, the emission measure of 10^{54-57} cm^{-3}, the e-folding time of 1 hour to 1.5 days, and the total radiative energy released during the flare of 10^{34-39} ergs.

3. A universal correlation between the flare duration and peak X-ray luminosity are discovered by Tsuboi et al. 2016 [3]. Moreover, they found that the data-points of the MAXI-detected flares lie on the extension of the established correlation between the flare-peak emission measure and temperature for solar flares and small stellar flares [4]. These correlations hold

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over a broad range of energies, from solar micro flares to large stellar flares. It suggests some common mechanism working in flare-triggering and cooling processes.

4. Although most of the flare sources are multiple-star system, single stars also showed large flares. These results indicate that neither binarity nor accretion, nor star-disk interaction is essential to generate large flares.

5. The flares, which MAXI detected, are occurred from limited number of active stars repeatedly, and most, so called "active stars" are quiet in MAXI's monitoring. It is notable that the most energetic flare source in the MAXI sample is the quadruple system GT Mus, which is located at about 150 pc distance.

6. From GT Mus, eleven flares were detected with MAXI. The flare parameters (kT, EM, $L_{\rm X\_bol}$, and $\tau_{\rm d}$) are found to be located at the upper end of the known parameter-correlation plot of stellar flares [3], suggesting that these flares have the largest energy (1–8 $\times$ 10^{38} erg) ever observed in history from stellar flares.

7. The follow-up X-ray observation of GT Mus with NICER suggests that the flare cooled quasi-statically (Sasaki et al. 2020 [15]). The flare loop size is estimated to be 5.1$\pm$0.4 $\times$ 10^{12} cm (73$\pm$6 $R_\odot$). This size is by two orders of magnitude larger than that of the typical solar-flare loop of 10^9–10^{10} cm.

8. GT Mus is plotted on the same trend with late-type main-sequence stars in the diagram of the X-ray to bolometric luminosity ratio against the Rossby number. On the other hand, GT Mus shows a considerably higher $L_{\rm X}/L_{\rm bol}$ than other giant binaries in the diagram. This high X-ray fraction suggests that GT Mus is at a high magnetic activity level, which is consistent with what is inferred from its recurring large flares.

DISCUSSION

DMITRY BISIKALO: What is the spatial resolution of your instruments?

YOHKO TSUBOI: The Point Spread Function of MAXI/GSC is 1.5 degree in FWHM. However, if we do the two-dimensional image fittings [19], we can determine the source location more precisely. The shape of the error region can be approximated with an ellipse with the typical semi-major and semi-minor axes of 0.7 degree and 0.5 degree, respectively, at 90% confidence level. We found that almost all the error regions contain only one stellar candidate listed in the ROSAT bright source catalog [20].

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