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On the morphology of outbursts of accreting millisecond X-ray pulsar Aquila X-1

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HIGHLIGHTS

- The X-ray light curves of the last two outbursts – 2014 & 2016 – of Aquila X-1 is presented.
- The relation between the peak intensity and the quiescent duration is investigated.
- We found that the outbursts following longer quiescent episodes tend to reach higher peak energetic.

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ABSTRACT

We present the X-ray light curves of the last two outbursts – 2014 & 2016 – of the well known accreting millisecond X-ray pulsar (AMXP) Aquila X-1 using the monitor of all sky X-ray image (MAXI) observations in the 2–20 keV band. After calibrating the MAXI count rates to the all-sky monitor (ASM) level, we report that the 2016 outburst is the most energetic event of Aql X-1, ever observed from this source. We show that 2016 outburst is a member of the *long-high* class according to the classification presented by Güngör et al. with $\sim$ 68 cnt/s maximum flux and $\sim$ 60 days duration time and the previous outburst, 2014, belongs to the *short-low* class with $\sim$ 25 cnt/s maximum flux and $\sim$ 30 days duration time. In order to understand differences between outbursts, we investigate the possible dependence of the peak intensity to the quiescent duration leading to the outburst and find that the outbursts following longer quiescent episodes tend to reach higher peak energetic.

1. Introduction

Aql X-1, discovered by Kunte et al. (1973) , is a low mass X-ray binary (LMXB) in which a neutron star accretes matter from a disk fed by its K-type companion via Roche lobe overflow (Frank et al., 2002). It displays thermonuclear X-ray bursts (Koyama et al., 1981) every few hours due to accumulation of matter on its surface. The burst oscillations (Zhang et al., 1998) as well as the measured spin frequency of 550.273 Hz (spin period is 1.8 ms) (Casella et al., 2008) indicate to a rapidly spinning neutron star likely spun up in accordance with the recycling hypothesis (Alpar et al., 1982). The detection of pulsations only during a limited episode indicates the object is an intermittent AMXP.

Aql X-1 is also classified as a soft X-ray transient (SXT) (see Campana et al., 1998, for a review) as it shows outbursts almost each year in its X-ray light curve due to the thermal-viscous instability in the accretion disk (see Lasota, 2001, for a review). We have a wealth of data of these outbursts thanks to the ASM aboard the Rossi X-ray timing explorer (RXTE) which monitors the source since 1996 until the end of the mission, and to the MAXI aboard international space station (ISS) for ongoing observations since 2009. These continuous observations allow Aql X-1 to be a suitable source for studying the outbursts of SXTs.

The morphology of the outbursts of Aql X-1 has been studied by Maitra and Bailyn (2008) via optical and near-infrared observations. They identify two types of events; the fast-rise-exponential-decay (FRED) type outbursts that are mostly explained with the disc instability model (DIM) (Lasota, 2001; Chen et al., 1997) and the low-intensity-state (LIS) events in which the structures of these outburst are in a more complicated variable flux state. which does not exceed the 5 cnt/s level and can last longer than a month.

A broad classification of the FRED type outbursts of Aql X-1 is presented by Güngör et al. (2014) (hereafter G14) who showed that FRED type outbursts of Aql X-1 exhibit three main classes depending on the peak flux and the outburst duration: the *short-low*, the *medium-low* and the *long-high* outbursts. The underlying physical cause of the differences between these classes is still unclear.

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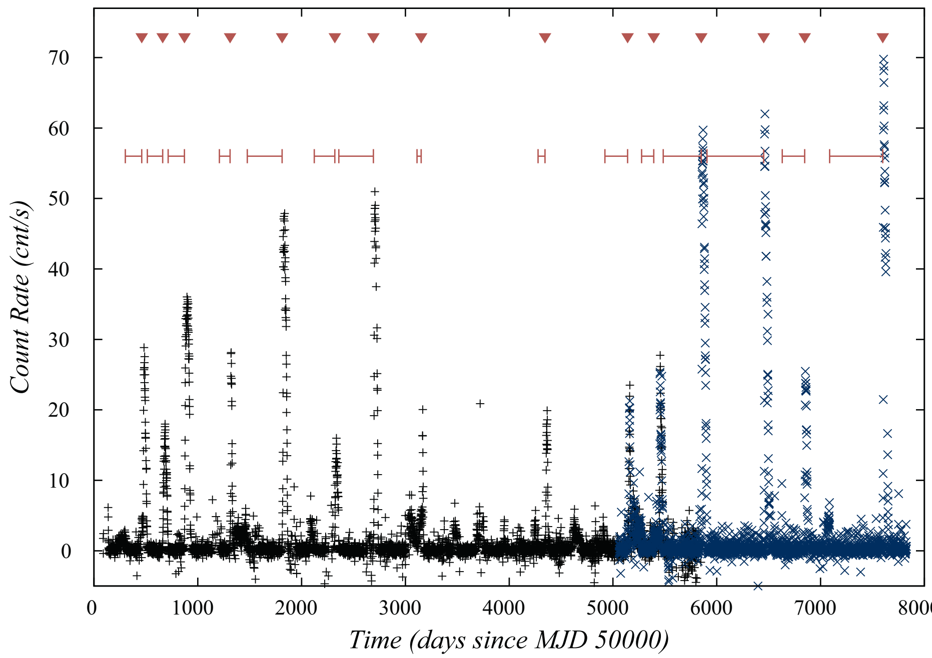

Fig. 1. 21 years light curve of Aql X-1 since 1996. The black pluses and the dark blue crosses represent the data obtained from the ASM and the MAXI, respectively. The brown upside-down triangles show the FRED type outbursts that are used in the classification study. The pre-outburst quiescent period for each outburst is indicated with the brown lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

We present the X-ray light curves of the 2014 and the 2016 outbursts in the light of the classification of G14 in Section 2. We explain, in that section, the procedures that we followed to define the outbursts and the durations of the quiescent stages, and the relation between them. We discuss and present the conclusions of our work in Section 3.

2. Methodology and results

We, first, obtained all daily average fluxes from the MAXI (Matsuoka et al., 2009) and the ASM in the energy range of 1.3–12.1 keV and 2–20 keV, respectively. These bands are the largest ranges for each detector. Following G14, we calibrated the MAXI data with the ASM data using the peak count rate of the 2009 and the 2010 outbursts which were observed by both detectors. In Fig. 1, we present the long term light curve of Aql X-1 displaying all the outburst of the source since 1996.

We, then smoothed the light curves of the 2014 and the 2016 outbursts with a "natural" spline formalism (Wahba, 1990) as done for the earlier outbursts in G14. In Fig. 2, we present the set of Aql X-1 outburst morphologies. Correspondingly, based on the outburst classification scheme of G14, we find that the 2014 and the 2016 outbursts fit into the *short-low* and *long-high* types, respectively.

We also investigated the possible relation between outburst characteristics and time passed prior to the onset of the activity. The essential step in this investigation was to establish a scheme to define the onset and the end of outbursts. We first selected time intervals with no activity to determine the average count rate and its standard deviation for the quiescent level. Assuming the 3σ level above quiescence as the threshold to identify a physical change in the light curve, we mark the beginning and the end of outbursts as the first and the last excess above the threshold level, respectively. We also require an outburst episode to have at least five individual measurement for a reliable identification. The brown horizontal lines in Fig. 1 indicate the intervals of pre-outburst quiescent stages for FRED type outbursts, and the upside-down triangles mark the onset times of these outbursts.

We find that the maximum intensity of Aql X-1 outbursts is positively correlated with the length of quiescent episode prior to that particular outburst. We present this correlation with square symbols in Fig. 3. Quantitatively, we obtain a Spearman's rank order correlation coefficient of 0.81 with the chance probability of 4.8×10^{-3} for the correlation between pre-outburst quiescent duration and the peak flux for FRED type of outbursts. We also fit the peak intensity vs. waiting time trend of these types outbursts with a first order polynomial, which yields a minimum peak rate of 7.9 cnt/s and the slope of 0.109 ± 0.023. Note that such a correlation is not the case for the much lower intensity LIS type nor for FRED+LIS type of outbursts.

3. Discussion & conclusion

In this study, we updated the classification introduced in G14 by adding the latest two outbursts – 2014 and 2016 – (Fig. 2) of Aql X-1 to the list. We showed that the outburst starting at July 2014 with almost 30 days duration and 25 cnt/s maximum flux is a member of the short-low type, and the outburst starting at July 2016 with 60 days duration and 68 cnt/s maximum flux is a member of the long-high type. This lends credit to the view that the classification scheme introduced by G14 is robust.

The long-term evolution of the X-ray flux of Aql X-1 shows that the energy released varies from one outburst to another. Although it displays at least one outburst almost each year, we see that the system passed through a relatively quiet episode between 2003 June and 2011 December during when it showed no outburst brighter than 30 cnt/s (Fig. 1), but exhibited many LIS type low energetic events. This propounds that the accretion reservoir is diminishing relatively calmly resulting in low-energetic events rather than leading to FRED type outbursts.

To explore the underlying cause for the differences between outburst types, we searched for a relation between the maximum intensity of the outbursts and the durations of the preceding quiescent episodes. We considered both the FRED and the LIS type events to identify the active and quiescent stages, therefore, we

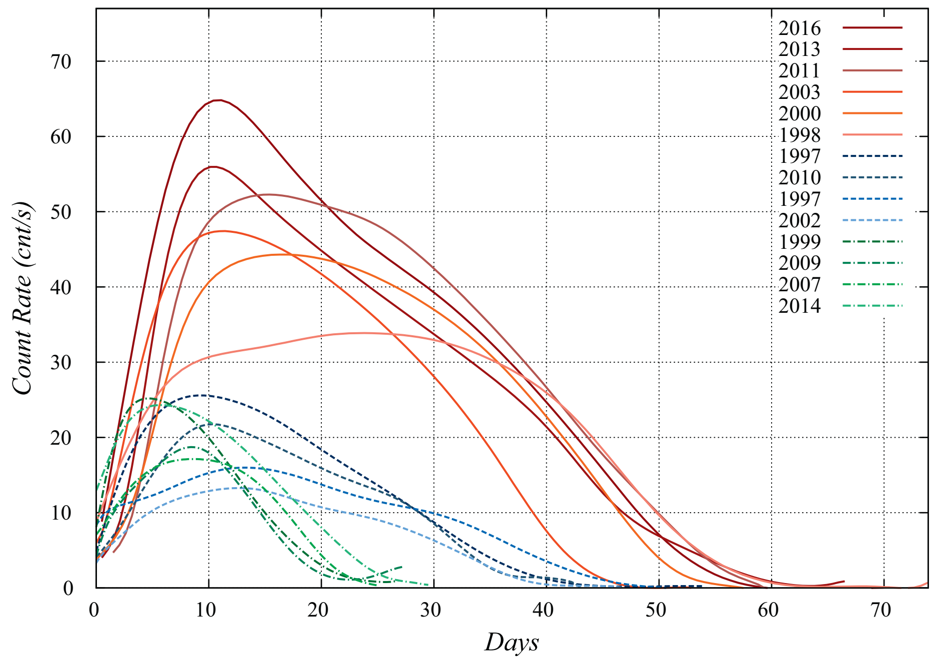

Fig. 2. The smoothed light curves of the outbursts of Aql X-1, calibrated based on the beginnings of the outbursts. This figure is an updated version of the one presented by G14 with the addition of the 2014 and 2016 outbursts. The labels from the top downwards represent the peak fluxes in order of maximum brightness.

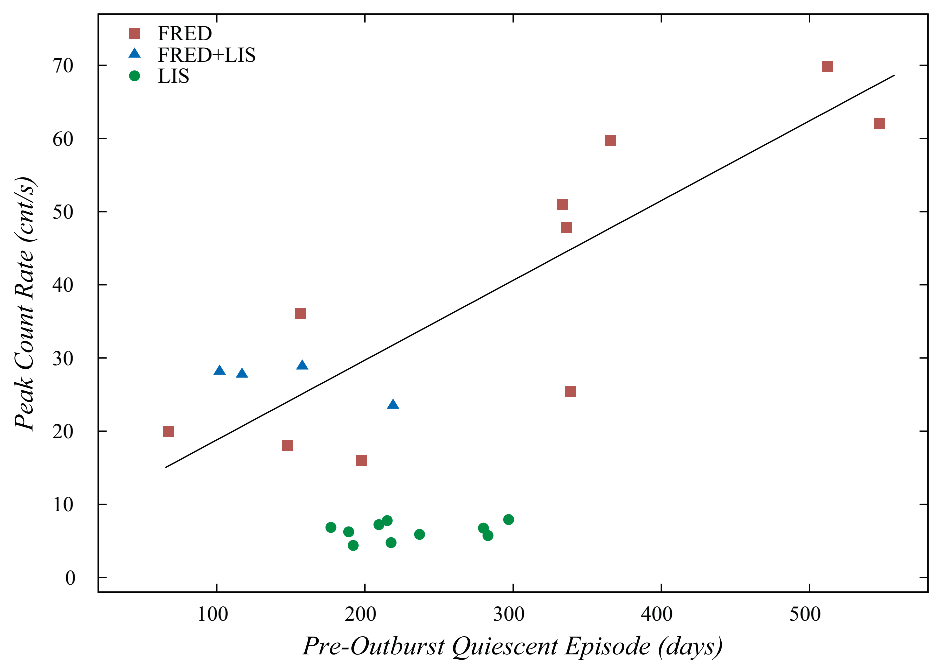

Fig. 3. The relation between the peak fluxes of the outbursts and the durations of the pre-outburst quiescent episodes. The brown squares, the blue triangles and the green circles represent the FRED type outburst, the FRED type outbursts with LIS companion and the LIS type outbursts, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article)

took into account the released energy even via weaker events. Thereby, unlike Campana et al. (2013), we introduce possible relation between peak fluxes of the outbursts and the durations of the preceding quiescent episodes as can be seen from Fig. 3. The scattered nature of the data in Fig. 3 around the linear fit implies that the waiting time is not the only parameter determining the energy to be released in the forthcoming outburst. On the other hand, we observe that the peak fluxes do slightly increase with the durations of the quiescent episodes. In this case, the longer waiting time might lead to accumulation of more material in the disc resulting in a more luminous outburst.

Finally, using the ratio of the peak count rates of the 2016 and 1997 outbursts, and the given peak luminosity of the 1997 outburst in Campana et al. (2014), the peak luminosity of the brightest outburst of Aql X-1 in 2016 is estimated as $\sim 8.7 \times 10^{37}$ erg/s (the distance of the source is 4.5 kpc (Galloway et al., 2008)). This corresponds to a peak luminosity $\sim 0.5\ L_{Edd}$ for a 1.4 $M_{\odot}$ neutron star accretor, after about 512 days of quiescence.

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