Mining the Aql X-1 long term X–ray light curve

S. Campana1,⋆, F. Coti Zelati1,2, P. D’Avanzo1
1 INAF-Osservatorio astronomico di Brera, Via Bianchi 46, I–23807, Merate (LC), Italy
2 Università di Milano-Bicocca, Piazza della Scienza 3, I–20126 Milano, Italy

11 May 2014

ABSTRACT
Aql X-1 is the prototypical low mass X–ray binary transient. The Rossi X–ray Timing Explorer All Sky Monitor provided a ∼16 yr coverage revealing 20 outbursts. This is by far the most extensive legacy of outbursts from the same source. We investigated the outbursts characteristics in terms of energetics, peak luminosities, durations, decays and recurrence times. We found that bright outbursts (peak luminosity ∼ 10^{37} erg s^{−1}) equal in number dimmer outbursts (< ∼ 10^{36.6} erg s^{−1}). The peak luminosity does not correlate with outburst energetics, durations or quiescent times. We analysed the latest stages of the outbursts searching for exponential and/or linear decays. Light curve modeling led to constraints on the outer disk radius and enabled us to estimate the viscosity and the irradiation parameters. The former is larger than what has been obtained for other, shorter orbital period, transients, while the latter is somewhat smaller. This might be related to the longer orbital period of Aql X-1 with respect to other transient X–ray binaries.

Key words: Stars: individual: Aql X-1 – X–rays: binaries — binaries: close — accretion disc — stars: neutron

1 INTRODUCTION
Aql X-1 is the most prolific neutron star low mass X–ray binary transient (LMXTs). Seven outbursts were observed by the Vela 5B satellite between 1969–1976 (Priedhorsky & Terrell 1984). The Ariel 5 satellite detected three outbursts in the 1976–1979 time period. Three more outbursts were detected by the All-Sky Monitor (ASM) on board the Ginga satellite in the 1987–1992 time frame (Kitamoto et al. 1993). Despite this high number of events, the sky coverage was not complete and some outbursts might have been lost. Interestingly, the recurrence period of the outbursts was short in the seventies, around 125 d (Priedhorsky & Terrell 1984), but it became longer in the eighties, around 300 d (Kitamoto et al. 1993).

The Rossi X–ray Timing Explorer (RXTE, 1996–2012, Levine et al. 1996) and more recently the Monitor All-sky X–ray Image (MAXI, 2009–now, Matsuoka et al. 2009) All-sky Monitors are continuously surveying with higher sensitivity the X–ray sky. Up to Sept. 2011, the RXTE/ASM detected twenty outbursts from Aql X-1 (two in common with MAXI). These data provide a unique database for investigations on outburst recurrence times and energetics.

The limiting sensitivity of RXTE/ASM is such that in the case of Aql X-1 we can follow the outburst decay down to a 2–10 keV luminosity of ∼ 5 × 10^{35} erg s^{−1} (at a distance of 5 kpc; Jonker & Nelemans 2004). In the case of MAXI we can reach a somewhat better (within a factor of two) limiting sensitivity. In addition to the possibility of detecting faint outbursts, this luminosity is sufficiently faint to allow us to investigate the outburst’s decay law. King & Ritter (1998) showed that X–ray heating during the decay from an outburst causes the light curves of LMXTs to show either exponential or linear decays, depending on whether or not the X–ray luminosity is sufficiently high to keep the outer disc edge hot. The rationale behind this is that if the disc’s outer portion is hot the entire disc is hot and matter can be efficiently transferred to the compact object, delivering a fast drain of the accretion disc.

In this paper we exploit the RXTE/ASM (and MAXI) database on Aql X-1. In Section 2 we discuss the data and characterise the outbursts. In Section 3 we focus on correlations among outburst properties and we fit the decay profiles of the outbursts to derive the outer disc radius (Section 4). In Section 5 we discuss our results.

2 DATA ANALYSIS
2.1 RXTE data
The RXTE/ASM consisted of three position-sensitive Scanning Shadow Cameras (Levine et al. 1996). RXTE started operating in Jan. 1996. The satellite was slowly spinning, observing sources for 90 s (dwell) during the 96 min duration of...
each orbit. Raw data points provided the fitted source rates in the 1.5–12 keV energy band. One-day averages are more commonly used, resulting from the average of the fitted source rates from the dwells during that time interval (typically 5–10). Each measurement (count rate) has an error associated, coming from the quadrature average of the estimated errors on the individual dwells. The one-day average light curve of Aql X-1 is shown in Fig. 1 (the flux of the Crab is \( \sim \) 75 count s\(^{-1}\)).

**2.2 MAXI data**

The MAXI is a position-sensitive X-ray all-sky monitor instrument, to scan almost the entire sky during its orbit, once every 96 minutes (Matsuoka et al. 2009). MAXI is located on the International Space Station and is collecting data since Aug. 2009. The detection sensitivity is somewhat better than RXTE/ASM, reaching a few mCrab during one day observations. The operational energy range is 2–20 keV. The one-day average light curve of Aql X-1 is shown in Fig. 2 (the flux of the Crab is \( \sim \) 3.5 count s\(^{-1}\) cm\(^{-2}\)).

**3 OUTBURST ANALYSIS**

During the Jan 1996 – Sep 2011 time interval 20 outbursts from Aql X-1 were recorded by RXTE and MAXI. Usually
the morphology of LMXTs is characterised by a fast rise and an exponential decay shape (Chen et al. 1997). In systems like Aql X-1, i.e. neutron star X-ray binary transients, the thermal viscous disc instability model (DIM; Lasota 2001) is usually considered to explain the transient behaviour. However, it has been shown that the DIM alone cannot reproduce FRED-like outbursts. The other key ingredient is X-ray irradiation. The irradiation of the outer parts of the accretion disc is caused by the intense X-ray flux produced from the innermost disc regions and from the neutron star itself. Irradiation dominates and heavily changes the outer disc temperature profile.

X-ray irradiation is also responsible for the decay of the outburst. If the outer disc edge is kept hot (i.e. above the temperature of the DIM hot viscous state), accretion disc theory predicts an exponential decay for the outburst (King & Ritter 1998). On the contrary if (or when) disc irradiation is not strong enough, the outer disc edge temperature falls below the limiting hot temperature of the DIM, and we can expect a linear decay of the X-ray flux.

We have analysed and characterised all the 20 Aql X-1 outbursts observed by RXTE/ASM. For each one of them we have first classified the outbursts, following Maitra & Baylin (2008). Outbursts were classified based on their X-ray morphology as: i) Fast Rise Exponential Decay (FRED); ii) FRED with peak(s); when overlaid to the FRED morphology there are pronounced peaks; iii) multi-peaks: when the presence of many peaks distorts the overall morphology; iv) Gaussian (Gaus): when the rise and decay times are more similar. The typical observed (e-folding) FRED rise times are approximately few days (up to a week) and the decay times are 3–4 weeks. According to Wachter et al. (2002), we observe that usually, following an outburst (but sometimes also preceding an outburst), the source might remain stuck in a low-intensity state (LIS), before ending (starting) the outburst. Outbursts are classified according to this scheme in Table 1. A few examples are shown in Fig. 3.

Table 1. Aql X-1 outbursts.

| Outburst     | Morphology | Duration (d) | Day Peak (MJD) | Rate peak (mCrab) | Rise (d) | Decay (d) | Quiescent time* (d) | Energy (10^34 erg) |
|--------------|------------|--------------|----------------|-------------------|----------|-----------|---------------------|-------------------|
| 1996 Feb     | FRED       | 9            | 50136          | 87                | 1        | 8         | –                   | 1.1               |
| 1996 May-Aug | Multi-peak | 95           | 50298          | 38                | 15       | 21        | 81                  | 7.6               |
| 1997 Jan-Mar | LIS-FRED-P | 90           | 50483          | 379               | 8        | 30        | 120                 | 21.7              |
| 1997 Aug-Sep | Gaus-P     | 64           | 50684          | 220               | 28       | 36        | 126                 | 12.6              |
| 1998 Feb-May | Multi-peak | 85           | 50885          | 482               | 19       | 40        | 145                 | 27.6              |
| 1999 May-Nov | FRED-P-LIS | 184          | 51320          | 376               | 12       | 172       | 358                 | 21.5              |
| 2000 Sep-Nov | FRED-P     | 58           | 51841          | 628               | 12       | 28        | 318                 | 36.0              |
| 2001 Jun-Aug | Multi-peak | 58           | 52087          | 65                | 16       | 42        | 203                 | 3.7               |
| 2002 Feb-Apr | FRED-P     | 60           | 52337          | 209               | 27       | 33        | 181                 | 12.0              |
| 2003 Feb-Apr | FRED       | 64           | 52706          | 649               | 20       | 44        | 316                 | 37.1              |
| 2004 Feb-Jun | LIS-FRED   | 130          | 53167          | 259               | 8        | 13        | 360                 | 14.8              |
| 2005 Mar-May | FRED-P     | 70           | 53473          | 66                | 23       | 47        | 270                 | 3.8               |
| 2005 Nov     | FRED       | 24           | 53692          | 68                | 6        | 12        | 160                 | 3.9               |
| 2006 Jul-Aug | FRED-P     | 40           | 53952          | 57                | 7        | 16        | 236                 | 3.3               |
| 2007 May-Jun | Multi-peak | 54           | 54254          | 64                | 24       | 30        | 250                 | 3.7               |
| 2007 Sep     | Gaus       | 36           | 54364          | 257               | 24       | 12        | 56                  | 14.7              |
| 2008 May-Jun | FRED-P     | 150          | 54627          | 55                | 32       | 73        | 174                 | 3.1               |
| 2009 Mar-Apr | FRED-P     | 40           | 54906          | 44                | 6        | 34        | 200                 | 2.5               |
| 2009 Nov-Dec | Gaus-P     | 38           | 55163          | 311               | 23       | 15        | 200                 | 24.9              |
| 2010 Sep-Oct | FRED       | 60           | 55453          | 349               | 13       | 47        | 262                 | 27.8              |

* Quiescent time before the start of the outburst.

We then investigated outburst characteristic times. The duration of an outburst is simply computed as the time difference between the first and last detection of a given outburst detected by the RXTE/ASM or MAXI (the latest two, see Table 1). The day of the outburst peak is reported in Table 1. We also consider rise and decay times. In order to be model independent, we prefer to separately indicate the time needed to reach the outburst peak (rise) and the time needed to reach non-detection (decay). In the case of a typical FRED-like (or Gaussian-like) outburst, the sum of the rise and decay times gives the outburst duration time. This is not the case when other main peaks are present or when there is a LIS.

We fitted each outburst profile with simple models in order to get a description of their overall shapes. A few of them are shown in Fig. 3. It is clear that outbursts can be very complicated and the analytical description does not provide a detailed account of all the small variations observed in the light curve. For this reason the reduced χ^2 obtained from the fit are often much larger than unity. Despite this, we verified that the overall fit we considered is able to account for the total energetics of the outbursts to a ~ 10% precision (this has been done for a few outburst cases, integrating point by point the light curve and extrapolating the data when observations were missing and comparing the results with the integral of the analytical function). To derive the outburst energetics we simply assumed a Crab-like spectrum. Knowing the source distance (5 kpc) and the column density can convert count rates into luminosities.
4 OUTER DISC RADIUS ESTIMATE

The late-stage light curve of LMXT outbursts are often characterised in terms of exponential or linear decays. If the outer disc edge is kept hot (i.e. above the temperature of the DIM hot viscous state), accretion disc theory predicts an exponential decay for the outburst, otherwise the decay is predicted to be linear (King & Ritter 1998). King & Ritter (1998) noticed that the exponential decay must revert to the linear mode when the X-ray flux has decreased sufficiently, but did not analyse this in detail. Powell, Haswell & Falanga (2007) took into account the continuous mass transfer into the disk from the donor star, and rewrote the total central mass accretion rate equation for the decay outburst profiles.

When the maximum disk radius of the hot viscous portion of the disk, \( R_0 \), becomes smaller than the total disk radius, \( R_{\text{disk}} \), (i.e. when the outer part of the disk is no longer kept hot, viscous state by central irradiation), then \( R_0 \) will decrease linearly and, correspondingly the X-ray luminosity will turn from an exponential to a linear decay. When this occurs a distinctive knee in the light curve outburst decay can be expected (see also Shahbaz, Charles & King 1998).

At variance with the above outburst light curve fits, here we fit all the latest stages of Aql X-1 outbursts with a function

\[
N = (N_t - N_e) \exp \left( -\frac{t - t_e}{\tau_e} \right) + N_e
\]

for the exponential part, where \( N_e \) is the count rate corresponding to the limit of the exponential decay, \( N_t \) is the count rate at the knee, and \( \tau_e \) is the time-scale of the exponential decay. The linear decline is given by:

\[
N = N_e \left( 1 - \frac{t - t_e}{\tau_l} \right)
\]

where \( \tau_l \) is the time after the knee at which the (extrapolated) count rate goes to zero. The two functions join at the exponential/linear transition knee. This function fully exploits Powell et al. (2007) outburst decay theory. Based on a Crab-like spectrum, one can convert rates into luminosities and relate the outburst decay to physical quantities of the system. An example is shown in Fig. 4.

The rate \( N_t \) can be converted into a luminosity \( L_t \) and related to the outer disc radius as \( L_t = R_{\text{disk}}(L_t)^2 / \Phi \), where \( \Phi \) is a constant related to the disc irradiation properties. Current estimates of \( \Phi \) are in the range \((1 - 9) \times 10^{-15} \) cm\(^2\) s erg\(^{-1}\) (see Eq. 2 in Powell et al. 2007 and King & Ritter 1998). A different estimate of the outer disc radius comes from the exponential decay time. This is related to the radius as \( \tau_e = \frac{R_{\text{disk}}(\nu / \Phi)^2}{\nu^2} \), where \( \nu \) is the viscosity at the outer disc edge. An estimate of the viscosity parameter \( \nu \) is in the range \((4 - 10) \times 10^{14} \) cm\(^2\) s\(^{-1}\) (Powell et al. 2007; King & Ritter 1998).

Additional constraints on the outer disc boundary come from the fact that it must be larger than the circularisation radius (the radius at which matter in Keplerian orbit has the same angular momentum as at the first Lagrangian point) and smaller than the first Lagrangian point from the center of the primary. In the case of Aql X-1 with an orbital period of 18.97 hr (Welsh, Robinson & Young 2000), the circularisation radius is \( R_{\text{circ}} \sim 5.0 \times 10^{10} \) cm (assuming a mass ratio of 0.3) and the distance of the first Lagrangian point from the center of the primary is \( b_1 = 2.0 \times 10^{11} \) cm (Frank, King & Raine 2002).

Adopting the values usually reported in the literature for \( \nu \) and \( \Phi \), the outer disc radius is smaller than circularisation radius. Imposing the condition that \( R_{\text{circ}}(\tau_e) \) is larger than the circularisation radius, we can infer that \( \nu \gtrsim 9 \times 10^{15} \) cm\(^2\) s\(^{-1}\) for all radii derived from the exponential decay. Using this value for \( \nu \) all the derived radii are also smaller than the \( b_1 \) radius, consistent with expectations (see Fig. 4).

The same constraint can be applied to the luminosity radius \( R_{\text{circ}}(L_t) \). In this case we derive \( \Phi \gtrsim 8 \times 10^{-16} \) cm\(^2\) s erg\(^{-1}\). Again, imposing this value, all the radii are also consistent to be smaller than the \( b_1 \) radius (see Fig. 4).

Assuming these values for \( \nu \) and \( \Phi \) one can compare the two determinations of the radii with the two methods finding a relatively good agreement, with only a few outliers. Overall
there is a factor of $\sim 4$ variation in the estimated outer disc radii among different outbursts. This can be due to (small) variations in the outer disc radius, outer disc viscosity, or irradiation parameter.

### 5 DISCUSSION AND CONCLUSIONS

The outbursts from Aql X-1 observed by RXTE/ASM span a long time interval (Jan 1996 – Sep 2011). Twenty outbursts were recorded. Outbursts occur mainly in the FRED flavour and often with secondary maxima (see Table 1). Peak luminosities can be divided into two separated groups: 11 outbursts fall within $10^{37} - 10^{38.6}$ erg s$^{-1}$ and 9 within $10^{36.3} - 10^{36.6}$ erg s$^{-1}$ with no outbursts in between (factor of $\sim 3$ luminosity gap). Ideally one would expect a correlation between the outburst peak luminosity and the recurrence time but this is not the case (see Fig. 6). In Fig. 6 we also included outbursts from Vela 5B and Ariel 5 (Kitamoto et al. 1993). Due to the higher limiting fluxes of these instruments, all the old outbursts fall in the bright group. A weak correlation (4% probability, according to the Spearman rank test) is present among these two variables, including the RXTE outbursts and the Vela 5B and Ariel 5 ones (see Fig. 6).

One can also expect a correlation among the peak outburst luminosity and the total energy of the outburst. This is not the case as shown in Fig. 7. According to a Spearman rank correlation test, there is 23% of a chance correlation. This is due to the presence of $\sim 4$ long-lasting low peak luminosity outbursts with a large emitted energy as well as $\sim 1$ short-duration high peak luminosity low energetic burst. This indicates that the peak outburst luminosity is not a good tracer of the outburst energetics.

We model the outburst decays with a combination of exponential and linear functions following Powell et al. (2007).
the value obtained by Powell et al. (2007). These authors found $\nu \sim 4 \times 10^{14}$ cm$^2$ s$^{-1}$ (factor of $\sim 20$ smaller), considering short orbital period accreting millisecond pulsars. The value we derived is also somewhat larger than the one obtained by Shahbaz et al. (1998) for Aql X-1 (factor 3–5), based, however, on a simpler modeling. This might be related to the very long orbital period of Aql X-1, pushing the outer disc edge a factor of 10–100 out with respect to the systems considered by Powell et al. (2007). The only long orbital period system considered by Powell et al. (2007) is the bursting pulsar GRO J1744–28 ($P_{\text{orb}} = 11.8$ d), which is indeed characterised by a factor of $\sim 10$ longer exponential decay time, confirming the increasing trend of the viscosity for larger accretion disk outer edges.

The irradiation parameter is instead lower than current estimates: $(4–9) \times 10^{-15}$ cm$^2$ s erg$^{-1}$ based on King & Ritter (1998) or $1.3 \times 10^{-15}$ cm$^2$ s erg$^{-1}$ on Powell et al. (2007). Our value is consistent with the latter estimate (just a factor of $\sim 2$ lower), whereas longer orbital period systems, such as GRO J1744–28, are characterised by $\Phi \sim 10^{-15} - 10^{-14}$ cm$^2$ s$^{-1}$, indicating that irradiation effects play minor role.

Adopting our values for $\nu$ and $\Phi$ we found a good agreement among the two different outer radii estimates based on the outburst decay light curve fitting. From Fig. 5 it is apparent that, for common values of $\nu$ and $\Phi$, the outer radius can span a factor of $\sim 4$ variation among different outbursts.

Given our 20 yr baseline we can compute the mean mass accretion rate of Aql X-1, integrating the observed luminosity. The mean mass accretion rate is $\dot{M} \sim 7 \times 10^{15}$ g s$^{-1}$ (assuming a standard 1.4 $M_\odot$ and 10 km neutron star). Given the 18.97 hr orbital period, this value places Aql X-1 well within the unstable region of the Disc Instability Model (Lasota 2001).

Finally, we estimated a mean recurrence time for the system of $280 \pm 103$ d (1 $\sigma$). This is considerably longer than the early recurrence time ($\sim 125$ d) estimated by Friedorsky & Terrell (1984) and more in line with the estimate of $\sim 300$ d by Kitamoto et al. (1993; see also Simon 2002). We also note that dim outbursts (those with a peak luminosity lower than $10^{36.6}$ erg s$^{-1}$) are more regular with a recurrence of $256 \pm 47$ d (18% dispersion). With a frequency of 1.36 outbursts per year in the RXTE era, Aql X-1 is the most prolific neutron star transient in the Galaxy.

6 ACKNOWLEDGMENTS

We thank the referee for useful comments and suggestions. We thank Andrea Melandri for comments.

REFERENCES

Chen, W., Shrader, C. R., Livio M. 1997 ApJ, 491, 312
Frank, J., King, A. R., Raine, D. J. 2002, Accretion Power in Astrophysics. Cambridge University Press, Cambridge, UK
Hartman, J. M., Galloway, D. K., Chakrabarty, D. 2011, ApJ, 726, 26
Jonker, P. G., Nelemans, G. 2004, MNRAS, 354, 355
King, A. R., Ritter H. 1998, MNRAS, 293, L42
Kitamoto, S., Tsunami, H., Miyamoto, S., Roussel-Dupre, D. 1993, ApJ, 403, 315
Lasota, J.-P. 2001, NewAR, 45, 449
Levine, A. M., et al. 1996, ApJ, 469, L33
Maitra, D., Bailyn, C. D. 2008, ApJ, 688, 537
Matsuoka, M., et al. 2009, PASJ, 61, 999
Powell, C. R., Haswell, C. A., Falanga, M. 2007, MNRAS, 374, 466
Priedhorsky, W. C., Terrell, J. 1984, ApJ, 280, 661
Sakurai, S., et al. 2012, PASJ, 64, 72
Shahbaz, T., Charles, P. A., King, A. R. 1998, MNRAS, 301, 382
Simon, V. 2002, ASPC, 261, 549
Wachter, S., Hoard, D. W., Bailyn, C. D., Corbel, S., Kaaret, P. 2002, ApJ, 568, 901
Welsh, W. F., Robinson, E. L., Young, P. 2000, AJ, 120, 943

Figure 7. Outburst peak X–ray luminosity vs. total outburst energy. Red filled circles refer to RXTE/ASM and MAXI data during the time interval 1996-2011.