Accretion-powered Millisecond Pulsar Outbursts

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Abstract. The population of accretion-powered millisecond pulsars (AMSPs) has grown rapidly over the last four years, with the discovery of six new examples to bring the total sample to seven. While the first six discovered are transients active for a few weeks every two or more years, the most recently-discovered source HETE J1900.1−2455, has been active for more than 8 months. We summarise the transient behaviour of the population to estimate long-term time-averaged fluxes, and equate these fluxes to the expected mass transfer rate driven by gravitational radiation in order to constrain the distances. We also estimate an upper limit of 6 kpc to the distance of IGR J00291+5934 based on the non-detection of bursts from this source.

INTRODUCTION

Each of the known AMSPs have now been well-studied in followup observations, and a review of their observational properties can be found in [1]. Six of the seven are transients with outburst intervals of 2 or more years. However, activity of the most recently-discovered example, HETE J1900.1−2455 [2], has continued long beyond the usual active interval for the other six sources. The latest observation, on 2006 February 2, indicates that the source is still at approximately the same flux level as it was throughout the second half of 2005. The source is also unusual in that the pulsations are not detected consistently while the source is active [3].

Here we present a summary of the outburst history of the accretion-powered MSPs, in order to compare the long-term accretion rates. We also introduce a new method which can give an upper limit on the distance for sources where no bursts have been detected.

OBSERVATIONS AND ANALYSIS

We analysed observations of the AMSPs made with the Rossi X-ray Timing Explorer (RXTE). We used measurements of the persistent flux and peak flux of thermonuclear (type I) bursts (where available) tabled in the catalog of Galloway et al. (2006a, in preparation). The data were analysed with LHEASOFT version 5.3, released 2003 November 17. The persistent flux was measured by averaging the integrated flux from the best-fit absorbed blackbody plus power-law model in the energy range 2.5–25 keV, to spectra extracted separately for each PCU. We used a bolometric correction to the 2.5–25 keV flux based on absorbed comptt model fits to combined PCA and HEXTE data. The X-ray colors for individual AMSPs were relatively constant over each outburst, and so we adopted a constant correction for each source: XTE J1814−338, 1.86; SAX J1808.4−3658,
2.12; XTE J0929−314, 1.80; XTE J1751−305, 1.66; XTE J1807−294, 1.57; and IGR J00291+5934, 2.54.

RESULTS

We estimated the fluence for each outburst using public RXTE PCA and ASM measurements. For intervals where the outburst was not covered by PCA observations, we integrated the ASM intensities instead, using a linear cross-calibration between the PCA and the nearest 1-day average 2–10 keV ASM intensities. XTE J1807−294 and XTE J1751−305 lie towards the Galactic center, and a cataclysmic variable is within the 1° RXTE field-of-view centred on IGR J00291+5934. Thus, for those sources we subtracted out a baseline level of 10, 5 and 5 × 10^{-11} erg cm^{-2} s^{-1} respectively, which we attribute to contributions from diffuse background and/or unrelated field sources. The fluences derived by this method, scaled to give the estimated bolometric values, are listed in Table 1. We propagated the errors from the uncertainties on individual ASM/PCA measurements. We note that the calculated fluences were generally consistent with prior estimates, to within the uncertainties.

The time-averaged accretion rate driven by angular momentum loss arising from gravitational radiation from the binary is given by

\[ \dot{M}_{GR} \gtrsim 3.8 \times 10^{-11} \left( \frac{M_C}{0.1 M_\odot} \right)^2 \left( \frac{M_{NS}}{1.4 M_\odot} \right)^{2/3} \left( \frac{P_{\text{orb}}}{2 \text{ hr}} \right)^{-8/3} M_\odot \text{ yr}^{-1} \]  

where \( M_C \) is the minimum companion mass, \( M_{NS} \) the neutron star mass, and \( P_{\text{orb}} \) the binary orbital period. Because pulse timing allows measurement only of the projected semimajor axis \( a_X \sin i \), only a lower limit on \( M_C \) is available. Thus, on equating the time-averaged X-ray flux \( \langle F_X \rangle \) and \( \dot{M}_{GR} \), we derived lower limits on the distance \( d \) for the interval prior to each outburst (Table 1).

For the three sources with thermonuclear bursts, independent estimates of the distance can be made from the peak burst flux. Based on bursts observed by BeppoSAX, \[5\] estimated \( d = 2.5 \) kpc for SAX J1808.4−3658 or up to 3.3 kpc for a pure He burst. Similarly, \[6\] estimated \( d = 5 \) kpc for HETE J1900.1−2455 based on a burst observed with HETE-II. While the brightest burst from XTE J1814−338 was not conclusively shown to exhibit radius-expansion, the implied \( d < 8(10) \) kpc for \( X = 0.7(0.0) \) \[7\]. Based on these distances, or the limits from Table 1 for those sources with no detected bursts, we estimated the long-term averaged \( \dot{M} \) for each of the AMSPs (Fig. 1).

We note that the measured outburst fluences and intervals for SAX J1808.4−3658 indicate that \( \langle F_X \rangle \) (and hence \( \dot{M} \)) is decreasing steadily. Since the distance depends on the flux only to the \(-1/2\) power, the derived limit varied only by 30%, up to a maximum of 2.9 kpc (Table 1). IGR J00291+5934 is the only other source for which multiple outbursts have been identified, and the increasing outburst interval suggests that \( \dot{M} \) may also have been decreasing with time.

Markedly different behaviour has been exhibited by HETE J1900.1−2455 since its discovery in 2005 June \[2\]. Although the source was too close to the sun for observations during 2005 December and 2006 January, activity has apparently continued for more
### TABLE 1. Outburst properties and distance limits for the millisecond X-ray pulsars

| Source           | Outburst Start (MJD) | Interval (yr) | Fluence $\langle F_X \rangle$ | Distance limit (kpc) |
|------------------|----------------------|--------------|-------------------------------|----------------------|
| XTE J1807−294    | Feb 2003 52681       | > 7.1        | 3.1 ± 0.2 < 1.4               | 4.7                  |
| XTE J1751−305    | Jun 1998 50978       | > 2.4        | ...                          | (< 3.0) (6.2)        |
|                  | Apr 2002 52363       | 3.8          | 2.3 ± 0.3 1.9                | (7.8)                |
| XTE J0929−314    | Apr 2002 52376       | > 6.3        | 5.4 ± 0.3 < 2.7              | (3.6)                |
| SAX J1808.4−3658 | Sep 1996 50333       | > 0.67       | 7.7 ± 0.6 < 36               | 1.4                  |
|                  | Apr 1998 50911       | 1.58         | 5.2 ± 0.5 10                 | 2.5                  |
|                  | Jan 2000 51547       | 1.74         | 5.4 ± 1.7 9.8                | 2.6                  |
|                  | Oct 2002 52559       | 2.8          | 6.2 ± 0.4 7.0                | 3.1                  |
|                  | June 2005 53522      | 2.6          | 4.9 ± 0.6§ 5.9               | 3.4                  |
| IGR J00291+5934  | Nov 1998 51143       | > 2.9        | ...                          | (< 1.8) (4.3)        |
|                  | Sep 2001 52163       | 2.8          | ...                          | (1.8) (4.2)          |
|                  | Dec 2004 53341       | 3.2          | 1.63 ± 0.16 1.6              | 4.5                  |
| XTE J1814−338    | Jun 2003 52789       | > 7.4        | 2.99 ± 0.12 < 1.3            | 10.5                 |

* The epoch for the outburst prior to the first known is assumed to be earlier than the first ASM measurements (typically 1996 January 6 or MJD 50088).
† Bolometric fluence, in units of $10^{-3}$ erg cm$^{-2}$.
** Estimated time-averaged bolometric flux in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.
‡ The values or limits in parentheses are based on an assumed fluence for the outburst, in the cases where the fluence of only one outburst has been measured with any precision.
§ The fluence for the June 2005 outburst of SAX J1808.4−3658 was estimated from the ASM observations alone, since no public PCA data were available.

than 8 months. While the estimated $\dot{M}$ in outburst (based on the approximately constant flux level of $\approx 9 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$ since 2005 June 14 [8]) is just 2% $\dot{M}_{\text{Edd}}$ (for $d = 5$ kpc), continuing activity would make this the AMSP with the highest average $\dot{M}$ by far (Fig. 1).

**Distance upper limits for non-bursting AMSPs.** While thermonuclear bursts have not been detected from four of the AMSPs, we expect that this is because they have been missed in data gaps rather than being absent altogether, as in (e.g.) the high-field pulsars. RXTE is in a low-Earth orbit with a period of $\approx 90$ min, and suffers regular interruptions when observing most of the sky due to Earth occultations, as well as observations of other sources and passages through regions of high particle density, which introduce additional gaps. The AMSPs be arbitrarily distant, because the implied $\dot{M}$ would exceed the Eddington limit; we may however infer a lower limit, at which point the implied $\dot{M}$ would be high enough to produce sufficiently frequent X-ray bursts that it would be highly improbable that they would all be missed by the RXTE observations.

The key factors to determine the likelihood of burst detection are the time density of observations (duty cycle) and the underlying burst rate, which depends in turn on $\dot{M}$ and the H-fraction in the accreted fuel, $X_0$. Three of the four AMSPs in which no bursts have been detected are in “ultracompact” binaries with $P_{\text{orb}} \approx 43$ min. The Roche lobes in such tiny binaries cannot contain a main-sequence companion, indicating that the mass donors are evolved and (probably) H-poor (e.g. [9]). The expected burst recurrence times are thus very long due to the absence of heating from persistent H-burning between
Figure 1: Distribution of time-averaged $\dot{M}$ for the AMSPs. The shaded histogram shows the distribution for sources with distances measured from the peak flux of thermonuclear bursts; the other values are from lower limits on $d$. The estimated $\dot{M}$ for HETE J1900.1−2455 in outburst, based on the reported source flux and distance, is indicated. The top $y$-axis is in units of g s$^{-1}$.

The combination of very low expected burst rates for these sources, and low duty cycles for the PCA observations (e.g. 6.6% for XTE J1807−294) makes it difficult to constrain the distances. The duty cycle for the PCA observations of IGR J00291+5934, on the other hand, was higher, at 27%. Since the mass donor in this source is also thought to be H-rich, we expect the highest burst rate of all four sources with no detected bursts, and thus is the least likely to have missed all the bursts.

We generated plausible burst sequences for IGR J00291+5934 based on the cubic-spline interpolated flux evolution measured during the 2004 December outburst, with burst ignition conditions calculated as in [10], to which we refer the reader for further details. We adopted a grid of distances beginning at the lower limits in Table 1. We assumed a 1.4 $M_{\odot}$ neutron star with radius $R = 10$ km, giving a surface gravity $g = (GM/R^2)(1+z) = 2.45 \times 10^{14}$ cm s$^{-2}$ and redshift $1+z = 1.31$. We generated $10^4$ burst sequences for each value of $d$ and $X_0 = 0.1, 0.3, 0.5$ and 0.7. We fixed $Z_{\text{CNO}} = 0.016$ (equivalent to solar metallicity) throughout. We varied the start time of the first burst evenly within the first predicted burst interval, and also introduced a modest degree of scatter on the burst times, with a standard deviation of 0.13 hr. We then checked how many of the predicted burst times fell within the intervals during which the PCA was observing the source. We interpreted the fraction of trials which resulted in one or more detected bursts, as the probability that we could reject that set of parameters.

At the lowest value of $X_0 = 0.1$, the predicted burst rate was sufficiently low that the likelihood of missing any bursts present was high, even for distances as large as 8 kpc. However, for higher values of $X_0$, the higher $\dot{M}$ implied by such large distances made it
increasingly unlikely that we would have missed all the bursts. Thus, the likely distance limit became smaller. Since we expect the mass donor in IGR J00291+5934 is H-rich, we expect a source distance of no more than 6 kpc (Fig. 2).

**DISCUSSION**

We have derived distances or limits to the known AMSPs via analysis of RXTE observations. Based on the outburst history of the AMSPs, the next outburst expected is from XTE J1751−305, early in 2006. In both cases where more than two outbursts are known (SAX J1808.4−3658 and IGR J00291+5934), we find evidence that the long-term averaged flux is decreasing. For the two transients with independent constraints on the distance from the peak flux of photospheric radius-expansion bursts, SAX J1808.4−3658 and XTE J1814−338, the maximum lower distance limit derived from equating the average flux and $M_{GR}$ is just above the distance range derived from the bursts. We also derived an upper limit on the distance to IGR J00291+5934 of 6 kpc, based on the predicted burst rate and the duty cycle for the RXTE observations. Given a sufficiently high observational duty cycle, this method may be used to derive distance limits on other LMXBs where bursts have not been detected.

Finally, we note the discovery of HETE J1900.1−2455, the first “quasi-persistent” AMSP. As of 2006 February this source is still active, more than 8 months after its discovery. Although the estimated $M \approx 2\% M_{Edd}$ is significantly lower than the peak reached by most of the other transient AMSPs, the fact that activity is continuous indicates that the long-term time-averaged $\dot{M}$ of this source may exceed all the others. In that case, HETE J1900.1−2455 is the best candidate for the detection of gravitational waves from an AMSP.

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