Outbursts, State Transitions, and Periodicities Observed with the RXTE All-Sky Monitor

Alan M. Levine

"Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Results from the All-Sky Monitor (ASM) on the Rossi X-ray Timing Explorer are reviewed. A number of recurrent transient sources have been detected, while only a few previously unreported sources have been discovered. The ASM light curves show a wide variety of phenomena in general, and, in particular, those of transient sources show a wide range of properties. Examples are used to illustrate that the distinction between persistent and transient sources may be very unclear. The results of searches for periodicities in the ASM light curves are summarized, and other astrophysical investigations using ASM light curves are suggested. The latter include investigations of the possible causes of long-term quasiperiodic and chaotic variability, and comparative studies on the basis of the observed variability.

1. Introduction

The primary purpose of the All-Sky Monitor on the Rossi X-ray Timing Explorer is to alert the astrophysics community in a timely manner to the outbursts of transient X-ray sources and to changes of state of persistent sources. Another purpose, which some may be consider to be a byproduct, is to record long-term X-ray “light curves” for the detected sources. Here I review the results of a year and a half of operation of the ASM, with selected illustrative examples of light curves and other results. First, the instrument design, operation, and data analysis is briefly described to provide background useful in interpreting the results. The numbers and types of transient sources that have been detected so far by the ASM are then discussed. A selection of astrophysical investigations that may be supported by the ASM results is described. Finally, I give advice and encouragement on the use of ASM data and results.

2. Instrumentation and Operations

The ASM consists of three Scanning Shadow Cameras (SSCs) mounted on a motorized rotation drive. Each SSC contains a position-sensitive proportional counter (PSPC) that views the sky through a slit mask. The PSPC is used to measure the displacements and strengths of the shadow patterns cast by X-ray sources within the field of view, and to thereby infer the directions and intensities of the sources. Each SSC is sensitive in the energy range of approximately 1.5–12 keV, with on-axis effective areas of ~10 cm², ~30 cm², and ~23 cm² at 2, 5, and 10 keV, respectively, and with a 6° × 90° (FWHM) field of view.

The ASM is operated so as to obtain series of 90-s exposures, called “dwells”, during which the orientations of the SSCs remain fixed. The drive assembly rotates the structure holding the 3 SSCs by 6° between dwells so that large portions of the sky are eventually scanned during each orbit of the spacecraft. The sensitivity is typically ~30 mCrab (3σ) for a source in the central region of the field of view of an SSC for a 90-s exposure. Any given source is typically scanned 5 to 15 times over the course of a day, so that the sensitivity is of order ~10 mCrab on a daily basis.

A more extensive description of the instrument, operations, and data analysis may be found in Levine et al. [1].

3. Transient and Newly Discovered Sources

When the ASM first became operational, two sources were in outburst and were bright enough to be easily detectable. These outbursts were...
associated with the sources GRO J1744–28 and X1608–52 (see Figure 1). The ASM has since detected the outbursts of quite a few other sources. While the majority of these sources were previously known or were discovered by other means, three of these transient sources were newly discovered with the PCA, and two were newly discovered using the ASM. This small number of new transient sources was a surprise. Since the ASM is significantly more sensitive than previous X-ray monitors, we anticipated that more previously unknown sources would be found. The sources that have been discovered with the PCA include XTE J1856+053, XTE J1842–042, and XTE J1739–302, while XTE J1716–389 and XTE J1755–324 were discovered with the ASM.

The light curves of 6 selected sources which have been detected in outburst for limited periods of time are shown in Figure 1. As noted above, the bursting pulsar GRO J1744–28 and the LMXB X1608–52 were already in outburst at the beginning of the RXTE mission. The middle two light curves are of sources discovered with RXTE; one can see that XTE J1856+053 underwent two distinct weak outbursts, while only one outburst of XTE J1755–324 has been observed. The spectrum of XTE J1755–324 was very soft near the peak of its outburst, and in fact was softer than any other source in the galactic center region that can be detected with the ASM. Its spectrum hardened considerably as its intensity decayed. The light curve of the Rapid Burster (X1730–333) shows recurrent outbursts which are spaced by ∼200 and ∼240 days. This confirms earlier indications that the source tends to go into outburst about every six months [2], and indicates that the outbursts most likely occur quasi-periodically. The bottom panel of Fig. 1 shows the outburst behavior of Aql X-1 in the RXTE era. In addition to the two obvious outbursts, it appears that the ASM just caught the tail end of an outburst as it first became operational, and detected a “failed outburst” starting around MJD 50240.

A number of systems show outbursts which appear according to an underlying periodicity. For systems such as GX301–2, EXO2030+375, and GRO J2058+42, the outbursts are consistently detected, whereas in systems like 4U1145–619 and 4U0115+63 only a few outbursts have been detected. In the latter two sources, the outbursts are spaced at 187 d and 24 d, respectively. I should note that in GRO J2058+42 the outbursts occur every ∼55 d, while a spacing of ∼110 d is apparent in the light curve derived from observations with BATSE [3]. The light curves of 4U1145–619 and GRO J2058+42 may be seen in Fig. 2.

Some sources, such as GRS1915+105 and GRO J1655–44, have undergone relatively long-lived outbursts. Other sources, such as KS1731–260 and XTE J1716–389 (Fig. 2), would not be classified as transients on the basis of RXTE data alone, since their emission has persisted for the entire mission so far, but are nonetheless classified as transients since they were not detected in observations with other instruments on occasions prior to the launch of RXTE.

We further illustrate the muddiness of the distinction between transient and persistent sources with the light curves of Cen X-3 and Cyg X-3 (Fig. 2). One can see the large and unpredictable variation of the intensities of these two sources, which is not at all unprecedented among the so-called “persistent” sources. Persistent sources also show state changes, with the hard/soft transitions of Cyg X-3 being the archetype [4].

The ASM has also detected X-ray emission during gamma-ray bursts and provided data for burst localization. Early estimates of the numbers of gamma-ray bursts were low because of a lack of data on the X-ray intensity of bursts and because the long duration, often over 100 s, of bursts in the 2–12 keV band was not taken into account. Since the ASM typically rotates by 6° every 90 s, the effective sky coverage for events that last ∼100 s is of order twice as large as for events which last a small fraction of 90 s. Indeed, this factor made it possible for the ASM to obtain crossed lines of position from the 1997 August 15 and 1997 August 28 gamma-ray bursts.

4. Astrophysics from ASM Light Curves

In addition to alerting observers to interesting cosmic X-ray phenomena, the ASM light curves may be directly of use in astrophysical investiga-
Figure 1. ASM light curves (1.5–12 keV) of 6 sources showing transient outbursts. Each data point is the weighted average intensity of all of the intensity measurements obtained from 90-s observations taken on a given day. The intensity is given in units of the count rate corrected for location in the field of view and for differences among the 3 SSCs. The Crab Nebula, for reference, yields 75 cts/s. Modified Julian Date 50083 corresponds to 1996 January 1.
Figure 2. ASM light curves (1.5–12 keV) of 6 more sources. The light curves for GRO J2058+42 and XTE J1716–389 comprise 3–day average intensities; the other light curves comprise 1–day averages.
tions. One of the most obvious of these is a search for periodic variability that could reveal the orbital period of a system or some other interesting phenomenon. Another type of investigation is the comparative study of the variability of different sources. In this section, I suggest a few lines of investigation that are likely to be interesting.

We and others have searched for periodic signals in the ASM X-ray light curves with the use of FFTs and/or Lomb-Scargle transforms. Figure 3 shows examples of power density spectra constructed using FFTs. Significant signals are detected in the spectra of each of the four power density spectra. In the cases of X1624–490, AM Her, and LMC X-4, the periodicities were known prior to the RXTE era. The detection of the 3.09 h periodicity of AM Her was unexpected, in that the source is so weak (~1 mCrab) that it is not detectable from direct inspection of the light curve itself. In the case of Sco X-1, two peaks at periods near 37 days, stand out (also see [5]).

Table 1 includes a list of periodicities that have either been detected in our analyses of ASM data or have been reported in the literature based on ASM data. Most of these are unquestionably detected in the power density spectra that we have computed; a few appear, in our analyses, to be based on peaks of marginal significance when the generally high noise level at low frequencies is taken into account. The 2.6 d periodicity in GRO J1655–40 was reported by Kuulkers et al. [1] not on the basis of a feature in a power density spectrum, but on the basis of the detection of “dips” that occur at about the same orbital phase.

The quasiperiodic intensity variations seen in systems like Her X-1 and LMC X-4 are most likely caused by a tilted precessing accretion disk. The ASM light curve of SMC X-1 (see Fig. 4), GX17+2, and GX349+2, show flares on top of a relatively constant baseline. The Z sources GX5–1 and GX340+0 yield light curves which are better described by random variability within a limited intensity range rather than by a baseline with distinct flares. Finally, Cyg X-2 shows dips from a baseline that wanders in a quasiperiodic manner over a range of a factor of 3 or more in strength. From Figure 4 one can see that the light curve of Sco X-1 bears no resemblance at all to that of atoll sources like 4U1728–34.

Another result that begs for explanation is the large degree of variation of the profiles and durations of the outbursts of transient sources. The outbursts of 4U1630–47, GRS1915+105, GRO J1655–40, and GRS1739–278 are each quite different from any of the outbursts shown in Fig. 1. I can also mention that the light curves and periodic spectral variation of Cir X-1 must be telling us something of astrophysical importance, and dramatic spectral variations of Cyg X-1 likewise.

5. Conclusions

Observers and students of bright X-ray sources will find ASM data and results to be useful. The light curves can indicate good observing opportunities, and later, when interpretation is in order, can give context to “snapshot” observations. One can keep informed using the MIT and GSFC web pages [http://space.mit.edu/XTE and http://heasarc.gsfc.nasa.gov/docs/xte/XTE.html] which have notes on source activities as well as
the light curves. Detailed analyses of a number of the brighter sources will be interesting; the data are available to be downloaded and analyzed. These data include the individual intensity measurements from the 90 s dwells in each of three energy bands.

While I strongly encourage the use of ASM data, I should caution potential users to beware of the occasional individual measurement that is affected by a problem. Patterns in the results are often much more reliable than a single high or low measurement. Finally, our error estimates do not include contributions representing all systematic effects. The errors are undoubtedly underestimated for sources observed with other sources also present in the field of view. The systematic effects will be particularly obvious in long-term averages of measurements of weak sources. I would also encourage potential users to contact a member of the ASM team with any questions that may arise.

The results from the ASM have been obtained by the direct efforts of many individuals at MIT and GSFC and by the indirect efforts of many others. The author is grateful for all their contributions.

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Table 1
Periodicities detected with the ASM

| Source      | Period  | Origin            | Reference                      |
|-------------|---------|-------------------|--------------------------------|
| AM Her      | 3.094 h | orbit             |                                |
| Cen X-3     | 2.083 d | orbit             |                                |
| Cir X-1     | 16.6 d  | orbit (?)         |                                |
| Cyg X-3     | 4.78 h  | orbit (?)         |                                |
| EXO2030+375 | 46 d    | orbit             |                                |
| GX13+1      | 24.7 d  |                   | Corbet [9]                     |
| GX301–2     | 41.5 d  | orbit             |                                |
| Her X-1     | 1.7 d, 35 d | orbit, disk precession | Zhang et al. [10], Wojdowski et al. [7] |
| LMC X-4     | 1.4 d, 30 d | orbit, disk precession |                            |
| SMC X-1     | 3.89 d, ~60 d | orbit, disk precession | Zhang et al. [10], Wojdowski et al. [7] |
| Vela X-1    | 8.96 d  | orbit             |                                |
| X 0114+65   | 2.74 h, 11.7 d | n.s. rotation, orbit | Corbet & Finley [11] |
| 4U1538–52   | 3.73 d  | orbit             |                                |
| 4U1700–37   | 3.41 d  | orbit             |                                |
| X1822-37    | 5.57 h  | orbit             |                                |
| Cyg X-2     | 77 d    | superorbital      | Wijnands, Kuulkers, & Smale [12] |
| GRO J2058+42| 54 d    | 1/2 orbit (?)     | Corbet, Peele, & Remillard [13] |
| Sco X-1     | 37 d    | superorbital      | Peele & White [6]             |
| X0115+63    | 24.3 d  | orbit             |                                |
| X1907+097   | 8.38 d  | orbit             |                                |
| X1637+415   | 10.4 d  | orbit             |                                |
| 4U1145–619  | 187 d   | orbit             |                                |
| Cyg X-1     | 5.6 d   | orbit             | Zhang, Robinson, & Cui [16]    |
| X0726-260   | 34.5 d  | orbit             |                                |
| GRO J1655–40| 2.621 d | orbit             | Kuulkers et al. [8]           |
| X2127+119   | 17.1 h, 37 d | orbit, superorbital | Corbet, Peele, & Smith [17]   |
| X1624–490   | 21 h    | orbit             |                                |
| X Per       | 835 s   | n.s. rotation     |                                |

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Figure 4. ASM light curves (1.5–12 keV) for 6 more sources. For SMC X-1, only non-eclipse data were used to construct the light curve shown here. The light curves for SMC X-1 and LMC X-3 comprise 2-day average intensities; the other light curves comprise 1-day averages.