The Rossi X-Ray Timing Explorer

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RXTE has been operating for nearly 2 years and is planning the third. The spacecraft performance has been good and the three instruments are operating well. Observations have been made of the range of targets suitable for RXTE, including such different objects as accreting neutron stars and black holes, stellar flares, and supernova remnants. The goals of studying high time resolution and broad energy range and optimizing multi-wavelength participation are yielding important results. Oscillations found from low-mass X-ray binaries probably are signatures of the spin of the neutron stars and of the shortest orbital periods around the neutron stars. These are constraining neutron star parameters. Oscillation and spectral results from black hole candidates bring into the realm of possibility the possibilities of measuring the spins of the black holes and using X-ray data to test predictions of gravitation theory. Multi-wavelength observations are leading to identification of the locations of the X-ray emission regions and, in the case of the micro-quasars, to understanding of the mechanisms for jet formation. Recently faster observing response than originally planned has made possible some RXTE contributions to identification of gamma-ray bursts.

1. THE RXTE MISSION

The RXTE was launched 1995 Dec 30. During the next week instruments were turned on while the spacecraft was checked out and calibrated. The Guest Observer (GO) program officially began Feb. 1, 1996, although a few time critical observations were done during the in-orbit check out period for the instruments. Some targets of opportunity, in particular, GRO J1744-28, were observed. The transient, bursting pulsar had been discovered by BATSE before RXTE’s launch and interest in the unique object was high. Many Target of Opportunity (TOO) proposals had been accepted for the first 9 months of the GO program, but remarkably, this object was not envisioned and in fact there were no accepted proposals for a new, bright, pulsing transient. The User’s Group had ruled that requests for observation of TOOs not covered by accepted proposals could be carried out if the data were made public. Thus we started early on a substantial public data base. Our planners make special effort to work new objects into the schedule and to find when sources can best be observed. In the two ensuing years 297 GO proposals were carried out, 71 of them (24 %) as TOOs. The amount of good observing time was $3.52 \times 10^7$ s in 24 months, for a net efficiency of 56 %.

RXTE was planned to have features judged necessary to understand the bright variable X-ray sky. It should have effective time resolution capable of studying the dynamical time scales of neutron stars and stellar black hole candidates, that is, better than tenths of milliseconds. For this, the area should be large. In fact, the area flown was cut back to be marginally effective for some goals. It should have energy coverage of at least 2-200 keV. Galactic compact sources in the plane tend to have column densities that cut off the observations at lower energies. Cyclotron lines, synchrotron radiation, and inverse-Compton spectra require sensitivity up to energies of $\approx 100$ keV. Many spectra cut-off approaching $m_e c^2$, and it was impractical for us to achieve more than 200 keV within our constraints. Fast and flexible response would allow transient states to be studied and would facilitate multi-wavelength observations; these were also judged essential for this mission.

In the launched configuration, the Proportional Counter Array (PCA) has an open area of 6250 cm$^2$ and the High Energy X-ray Timing Experi-
Figure 1. Drawing of RXTE in orbit. The five PCA counters are in the openings protected by solar shields. The 3 ASM Scanning Shadow Cameras rotate on the boom on the left. The HEXTE clusters are hidden under the thermal blankets to the right of the PCA. They look out the same direction as do the PCA collimators, with the same field of view. Two oppositely directed antennas allow scheduled communication to proceed regardless of changes in the observation schedule.

The responses and resolutions of the detectors are nominal, except that because of an electronic failure, for 1 of 8 HEXTE detectors the pulse heights are not available. HEXTE does have a larger than expected dead time due to large particle events, which reduces the sensitivity. Activation of the PCA during passage of the SAA has complicated calibration of the background. Calibrations of background and response will still be improved, but are now good to a couple of percent. Papers presented in this volume attest to the ability to use the PCA and HEXTE together to measure cyclotron line characteristics and the spectra of active galactic nuclei (AGN).

Sources can be viewed with both the PCA and HEXTE when the bore-sights are farther than 30 degrees from the sun. This constraint is more relaxed than for most missions and has helped with the observations of transients and time critical behavior. Of course even this constraint can be frustrating. When GRO J1744-28 had a second outburst and for the second time BATSE saw that the first day’s bursts were of a different character than later, with only 3 minutes separation time, we were unable to make observations. Many monitoring observations have followed sources for the duration of the mission. Brief looks (1000 s minimum) are possible for campaigns of various durations and density. Observations shorter than that, while sufficient to determine flux well, turned out to stress the satellite slewing and attitude determination resources.

After the delivery of weekly observing plans, many re-plans are carried out to allow for TOOs and to change the observing plans on the basis of results. We had designed the system to the requirement that a new source could be observed within 7 hours of discovery. Within the regular planning process that is difficult, but such a rapid turn around is rarely optimal. However the Beppo-SAX discovery of the X-ray after-glow of Gamma-Ray Bursts has inspired development of much faster procedures, which lead to observations within 2-3 hours. We can slew directly to a source (at 6 degrees per minute), if commanding is available and there are no conflicting stored commands.

Figure 1 shows the satellite with the All Sky Monitor (ASM) on one end, comprising three one-
dimensional imaging proportional counters with coded masks that rotate around the boom on which they are mounted and survey 70 % of the sky. Solutions for the flux of each cataloged source are computed for each 100 s dwell in the step-wise rotation per satellite orbit of 90 minutes. Residuals to the fit indicate uncataloged sources.

The five detectors of the Proportional Counter Array operated flawlessly for about three months, at which time, the two detectors which operated at the coldest temperatures, within an orbit of each other suffered short-lived breakdown events. We have implemented the spacecraft’s capacity to "look" at the data being produced and take prescribed actions to turn high voltage off in less than a minute if a breakdown event is beginning. This, and operating the spacecraft slightly differently to keep the detectors warmer, have so far allowed us to keep operating without accelerated detector degradation. During the first months the ASM detectors lost 4 anode wires out of 24, due to high voltage breakdown. The work-around in the ASM case was to burn the conducting carbon off the affected anodes and to guard against operating at very high rates. Each wire is calibrated [5,6] and the results for a large number of sources can be found on the Web, on the MIT and the RXTE GOF pages: http://space.mit.edu/~derekfox/xte/ASM.html http://heasarc.gsfc.nasa.gov/docs/xte.

RXTEs targets include galactic compact stars, AGN, stars, supernova remnants, diffuse emission, and gamma-ray bursts. Galactic compact stars account for 80 % of the targets: accreting high magnetic field binary pulsars, accreting low-mass binary pulsars, rotation-powered pulsars, black hole (BH) candidates, and white dwarfs. In this paper I will describe results that have been obtained for these sources. Other papers in this volume describe some of the results on AGN and diffuse sources. References must necessarily be incomplete and my choices of examples could well be biased by my own associations.

2. RXTE RESULTS ON GALACTIC SOURCES

2.1. Low-Mass X-ray Binaries

The thermonuclear flash bursts have been convincing evidence that the compact object in bursters, and by extrapolation, Z and atoll low-mass X-ray binaries in general, is a neutron star. Yet it has remained uncertain why no pulsed flux had been seen. Surface fields of $10^9 - 10^{10}$ G fields are expected if the sources are progenitors of millisecond radio pulsars with such fields. The beat frequency model of the "Horizontal Branch" quasiperiodic oscillations of the Z sources implied such fields (e.g. [7]). Many aspects still remain uncertain and the beat frequency model is now in question. But the kilohertz oscillations that RXTE has discovered, in the persistent flux and in some of the thermonuclear flash bursts, are signatures that may identify the spin. These signatures, in a phase space not previously accessible, are a new light on the nature of all of the oscillations shown by these sources. It is clear that the dimensions and time scales are characteristic of the regions very close to the neutron star and that interpretation in terms of effects of strong gravity, like a marginally stable orbit [8,9], and possibly frame dragging [10] are quite possible. More than 15 sources exhibit the kilohertz oscillations [11] and 6 sources exhibit 300-600 Hz oscillations during bursts [12].

The characteristics of the oscillations and their interpretations are discussed extensively in other papers in these proceedings. The oscillations are sometimes either not present or difficult to discern, even in sources in which large amplitudes have been observed. Thus failure to discover them in one observation does not imply they will not appear in another. We believe the phenomena are characteristic of these sources.

In studying the correlation of the kilohertz oscillations with luminosity and source state, the transient bursters are useful. Outbursts of X1608-522 and Aquila X-1 have occurred which were identified with the ASM. Series of observations at different luminosity levels showed that the identification of the mode and its correlation with luminosity are not simple, but may involve different states of accretion [13,14]. There appear to be 2 ranges of luminosity in which an oscillation goes through the same frequency range.
2.2. Rotation-Powered Pulsars

The number of radio pulsars that are known to emit non-thermal pulsed X-rays is small. Yet medium energy X-rays are diagnostic of competing models of the generation of the pulses. RXTE started observing the Crab pulsar during the in-orbit check-out phase, and continues to monitor the pulsar for possible changes that may be associated with changes at other wavelengths. RXTE has made extensive observations of B1509-58 (150 ms) and also observed B1821-24 (3 ms) in order to check the time assignments of events and the timing software to a sub-millisecond accuracy [15,16]. The weight of the evidence is that absolute times are precise to 8 µs and some interesting small differences between peak times in the X-ray and radio are observed. Pulsars could have around them UN-pulsed synchrotron nebulae, as the Vela pulsar may. But the Vela pulsar has pulsed gamma-rays, pulsations recently identified in OSSE data, and pulsed soft X-rays seen with ROSAT. The pulses are nearly sinusoidal, except possibly during the brightest bursts themselves, when the saturation of the detectors by the high event rate [21] distorts the shape of the pulse. During the outburst peaks, the pulsed flux outside of the bursts was about twice as bright as the Crab, and if the source is as far as 7 kpc, about twice the Eddington limit (for cosmic abundances and a 1.4 M⊙ star) [22]. The OSSE data showed that during the bursts the pulses came late [23]. The PCA data showed that after the bursts, the pulse phase lagged behind and then gradually recovered between the bursts [24].

2.3. Soft Gamma-ray Repeaters

While only one of the 3 known soft-gamma-ray repeaters, SGR 1806-20, has been reported active during the first 2 years of RXTE, RXTE observations of it were spectacular [18]. Hundreds of very short bursts were detected, most a few millisecond in duration, some so bright as to be a hundred times the Eddington limit for a neutron star source, with a broad distribution in sizes and separations [17]. Low-level flux is seen between the bursts. Conclusions have not been announced, except that the spectra do not have any clear cyclotron feature [25].

2.4. Accreting Pulsars

Many observations of accreting pulsars have been carried out, in which pulse to pulse variations are evident in real time data. While some of these results have been presented at meetings, few have yet been published.

However the observations of the bursting pulsar GRO J1744-28 show some diagnostic effects. The pulses are nearly sinusoidal, except possibly during the brightest bursts themselves, when the saturation of the detectors by the high event rate [21] distorts the shape of the pulse. During the outburst peaks, the pulsed flux outside of the bursts was about twice as bright as the Crab, and if the source is as far as 7 kpc, about twice the Eddington limit (for cosmic abundances and a 1.4 M⊙ star) [22]. The OSSE data showed that during the bursts the pulses came late [23]. The PCA data showed that after the bursts, the pulse phase lagged behind and then gradually recovered between the bursts [24]. The behaviors of the pulse delay and the flux in recovering were similar, although the flux recovered more quickly. The bursts provide a sharp mechanism, apparently, that distorts the field configuration. Quasiperiodic oscillations in the pulsed flux were triggered by some bursts [28].

As the persistent flux subsided, the pulse period shortened gradually until it reached a plateau. Interpreted in terms of the transition between spin up and down, the field should be \(4 \times 10^{11} \text{ G} \) [22,26] and reduction in the pulsed flux may correspond to the centrifugal barrier to accretion [21].

GRO J1744-28 is in the galactic center region, subject to confusion at the level of one milli-Crab. Both RXTE and the WFC on BeppoSAX have seen that the region contains numerous little known burst sources. On the other hand, anomalous pulsars with periods near 7 s, only a few milli-Crab as well, are better isolated. Although their spectra are very soft and the PCA is less sensitive to such spectra than to the hard spectra exhibited by the bursting pulsar, strong constraints on possible binary orbit parameters are being obtained from upper limits to the Doppler shifts (for 1E 2259+586, \(\leq 0.03 \text{ lsec} \) [24,23]). Other observations may make it difficult to fit any companion star into the orbit without assuming the coincidence of a nearly pole-on view.
2.5. Black Hole Candidates

As the mass accretion rate through the disk onto accreting black holes increases, according to theory (e.g. [31]), the hydrodynamics of the flow and the state of the disk changes. For luminosities in the range of a few percent of Eddington, there is perhaps a corona of high temperature electrons which Compton scatter soft photons to a spectrum that approximates a power law with photon index 1.6 below about 30 keV. For luminosities tens of percent of Eddington, there is evidence for existence of an optically thick disk with $kT \leq 1$ keV, in ultra-soft transients. It often coexists with a non-thermal component which looks like a power-law (with photon index $\geq 2$) in the medium energy X-ray regime. Cygnus X-1 and other BH candidates have also exhibited some clear temporal signatures, notably excess aperiodic variance, power spectral densities, and time lags of higher relative to lower energies. The timing behavior, more than spectral uniqueness, appeared to define a very high state of accreting BHs, with accretion rate approaching the Eddington limit. Nova Muscae and GX339-4 are the two candidates for this state identified by GRANAT and Ginga. RXTE has observed all these states from BH candidates, although the classic soft and bright transient often associated with a BH, characterized by a fast rise and a 30 day e-folding time decline has not yet been seen. It is overdue, considering the 1 per year average of 1987-1995.

Cyg X-1 has been observed many times, for proposals with different goals; observations have different strategies and observing modes. It went into a soft state for $\approx 3$ months, anticorrelated with the hard X-ray flux measured by BATSE [32]. The power spectral density changed from band-limited white noise with hints of broad QPO features to a power law; the lag times changed from 0.01–0.1 s to $\leq 0.01$ s; the coherence between high (6.5-13.1 keV and above 13.1 keV) and the lower energies was near 1 except during the transitions between the soft and hard states, when it was 0.6–0.9. Coherence near 1 has been taken as witness that the same scattering function could be applied to all flares or shots. The long lag times in the low state and the transition states have been taken to imply an extended corona (e.g. [33]), more extended than in the soft state [34]. So far, a definitive report on the existence of millisecond bursts has not appeared, although the shot distribution includes a significant fraction of very short shots [35], whose existence may imply a more complex model than a central source of soft photons at the center of a large scattering cloud. Spectra have been modeled with several different approaches to the inverse-Compton scattering off high energy electrons (e.g. [36, 37, 38]).

The measurements of some known sources, in particular 1E1740-29 and GRS 1758-28 [39], and some new transients, of which GRS 1737-31 is a good example [40], show that both the spectral and temporal characteristics of Cyg X-1 are shared by other sources with luminosities about $10^{37}$ ergs s$^{-1}$.

Although no new very bright ($\geq 1$ Crab) BH transient has been discovered (by the ASM, GRANAT, the CGRO BATSE, the BeppoSAX WFC, or any other mission), the two recurrent transients GRO J1655-40, and GRS 1915+105 became bright in the first few months of the mission, and have had important impact on the RXTE mission. The visibility of the companion star to GRO J1655-40 has given a precise measurement of the mass of the compact object as $7 M_\odot$, making it one of the best established BH candidates. The similarities of the two sources [41], called micro-quasars because of the radio jets, makes it probable they are both BHs. Further similarities in the X-ray spectral parameters and in fast oscillations sometimes exhibited have suggested that these two sources may differ from others in the spin of the BHs [42]. The association of BH spin and jets fits in well with the possibility that AGN jet sources are associated with spinning BHs. For both these sources fast oscillations are sometimes observed [43] that could be the epicyclic frequencies in the disks around spinning BHs (with dimensionless angular momentum near 1) [44], or Lens-Thirring precession of the disks [45]. RXTE, infrared, and radio observations of GRS1915+105 have led to a detailed connection between disk instabilities and the injections into the jets [46, 47]. The association between X-ray dips and the appearance of ejected and cooling material has promise of being a break-through...
in understanding both Galactic BH sources and Quasars. It explains why jets contain discrete blobs.

The transient BH candidates that RXTE has observed in the first two years are listed in Table 1. The values given for recurrence and decay times and peak fluxes (of outbursts observed with RXTE) are only approximate.

| Source      | Recur Days | Decay Days | Peak Flux mCrab |
|-------------|------------|------------|-----------------|
| GRS 1915+105| 300        | 600        | 3000            |
| GRO J1655-40| 300        | 400        | 3000            |
| 4U 1630-47  | 600        | 150        | 300             |
| Cyg X-1     | 900        | 85         | 500             |
| GRS 1739-278| 150        | 700        |                 |
| GRS 1737-31 | 30         | 30         |                 |
| XTE J1755-324| 30       | 180        |                 |
| X1354-644   | 3600       | 60         | 50              |

**Table 1**

| Transient BH Candidates Seen with RXTE |
|---------------------------------------|

2.6. ASM Transients

The ASM and the PCA in scans are both detecting transients \(\geq 30 - 100\) mCrab, even in the Galactic Center region. They complement each other in that ASM identification leads to a PCA observation and the light curve of a source detected with the PCA can, after the fact, be determined with the ASM, even when it did not identify the source. Outside the Galactic Center, the ASM can detect sources like Mkn 501.

The ASM is giving a very much more complete record than available before of the behavior of transients, the low level in between outbursts, the small flares that fail to develop into major outbursts. There are many Be star pulsars active at low levels with recurrence times of months to years. Table 2 lists some that RXTE has seen. The ASM is also identifying much more clearly long quasi periods of LMXB and pulsars. At the level of 10 mCrab it is very sensitive to long time-scale periodic and quasi-periodic variations.

| Source      | Recur Days | Decay Days | Peak Flux mCrab |
|-------------|------------|------------|-----------------|
| GRO J1744-28| 300        | 200        | 2000            |
| 1RXS J1708-40| 60        | 200        |                 |
| X0115+63    | 111        | 10         | 60              |
| X1145-619   | 200        | 20         | 100             |
| GS 1843+009 | 50         | 26         |                 |
| GS 2138+568 | 20         | 50         |                 |
| EXO 2030+375| 30         | 5          | 40              |
| A 1833-076  | 20         | 6          |                 |
| GRO J2058+42| 53         | 8          |                 |
| 4U 0726-260 | 35         | 3          |                 |

2.7. White Dwarfs and Stars

The numbers of white dwarf sources, Dwarf Novae, Intermediate Polars, and Polars and of non-compact stars that are bright enough at hard X-rays for a collimated instrument like the PCA are smaller than the numbers of neutron stars, but there were 58 proposals carried out in the first two years. Some important results that depended on either the large area or the ability to carry out long monitoring campaigns have shown their power. The Intermediate Polar XY Ari is an eclipsing system and repeated coverage of the eclipse of the white dwarf was able to identify the source of the X-ray emission as small radius shells at the magnetic poles. Some of the observations caught the source going into outburst, and the changes in the pulsed fraction before the change in the luminosity give a detailed insight into the magnetic connection between the disk and the white dwarf. A very different source is \(\eta\) Carina, in which a set of Einstein Observatory, ROSAT, BBXRT, and ASCA observations over the last decade had identified a variable hard source with a thin-thermal spectrum as associated with the star itself in the extended dust cloud. The X-ray monitoring campaign found a long build up of X-ray flux to a drop coincident with UV and radio drops and consistent with the suggested 5 yr. period. The X-ray observations also found a still mysterious \(\approx 85\) day period.
3. CONCLUSION

RXTE has clearly been very successful for a variety of studies. The quantity and detail of the data make complicated systems like high magnetic field pulsars a challenge to analyze and complexity of the calibrations has daunted some observers initially. However, the results that have appeared are exciting and the good results from some observations of sources only a few mCrab in strength are inspiring. We look forward to many more anticipated results, to answering the deeper questions that observations have raised, and to observing more examples of the rare phenomena that we sometimes encounter that greatly improve our insight into high energy sources. Compared to the long run, the time these sources spend in some of the most interesting states is short, and there are few enough of them that the combination gives us relatively rare examples. We hope to use the hard won resources of RXTE and Beppo-SAX to be able to study as many of these as possible.

I would like to acknowledge the many people who have contributed in many ways to planning, building, launching, operating, and using RXTE.

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