An Extended and More Sensitive Search for Periodicities in Rossi X-ray Timing Explorer/all-sky Monitor X-ray Light Curves

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AN EXTENDED AND MORE SENSITIVE SEARCH FOR PERIODICITIES IN Rossi X-RAY TIMING EXPLORER/ALL-SKY MONITOR X-RAY LIGHT CURVES

ALAN M. LEVINE1, HALE V. BRADT1,2, DEEPTO CHAKRABARTY1,2, ROBIN H. D. CORBET3,4, AND ROBERT J. HARRIS5

1 Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA; aml@space.mit.edu, hale@space.mit.edu, deepto@mit.edu
2 Physics Department, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
3 University of Maryland, Baltimore County, MD, USA
4 X-ray Astrophysics Laboratory, Code 662, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA; robin.corbet@nasa.gov
5 Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA; rjharris@cfa.harvard.edu

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ABSTRACT

We present the results of a systematic search in ~14 years of Rossi X-ray Timing Explorer All-Sky Monitor (ASM) data for evidence of periodicities. Two variations of the commonly used Fourier analysis search method have been employed to significantly improve upon the sensitivity achieved by Wen et al. in 2006, who also searched for periodicities in ASM data. In addition, the present search is comprehensive in terms of sources studied and frequency range covered, and has yielded the detection of the signatures of the orbital periods of eight low-mass X-ray binary systems and of ten high-mass X-ray binaries not listed in the tables of Wen et al. Orbital periods, epochs, signal amplitudes, modulation fractions, and folded light curves are given for each of these systems. Seven of the orbital periods are the most precise reported to date. In the course of this work, the 18.545 day orbital period of IGR J18483–0311 was co-discovered, and the first detections in X-rays were made of the ~3.9 day orbital period of LMC X-1 and the ~3.79 hr orbital period of 4U 1636–536. The results inform future searches for orbital and other periodicities in X-ray binaries.

Key words: binaries: general – X-rays: stars

1. INTRODUCTION

We have extended the search of Wen et al. (2006) for periodicities in the intensities of cosmic X-ray sources using light curves produced by the Rossi X-ray Timing Explorer (RXTE) All-Sky Monitor (ASM). Wen et al. (2006) analyzed data accumulated during the first 8.5 years of the mission and detected 41 periodicities and 5 possible periodicities or quasi-periodicities. Two of the periodicities detected in their search likely represent neutron star spin and ~6 represent the precession of tilted accretion disks or other phenomena that produce superorbital periods. The 33 other periodicities are believed to represent evidence of the orbital motion of a close-binary star system. Most of the orbital periods were associated with high-mass X-ray binaries (HMXBs) each comprising a supergiant or a Be star and a compact object. Eight of the periodicities were associated with the orbital periods of low-mass X-ray binaries (LMXBs), and was one was associated with a cataclysmic variable.

The search of Wen et al. (2006) was one of the most comprehensive searches for periodicities in the range of hours to years in the X-ray intensities of the bright (~1 mCrab) Galactic X-ray sources. However, relatively few new periods were found in the course of the search in spite of the conventional wisdom that many of the bright Galactic sources are accreting binaries with periods in the range of sensitivity of the search. The orbital periods of many Galactic sources are still not determined, and so searches for evidence of these presently unknown orbital periods remain of interest.

The present search improves on the sensitivity achieved in the earlier search through the analysis of light curves obtained over a longer course of time, i.e., nearly 14 years as opposed to 8.5 years, and through several changes in the analysis procedures. We have also analyzed subintervals of the mission-long data sets. A preliminary report of the results of this work was presented in Levine & Corbet (2006).
of 571 potential sources for each of the four energy bands. The intensity measurements contained in these files are the input data for the present periodicity search.

The instrument properties have changed over the 14 years of operation in orbit because of at least three effects. First, the gain, i.e., the mean ratio of pulse height to photon energy, of the proportional counter in SSC 1 (of SSCs 1–3) increased at about 10% per year for the first 13 years or so because of a leak in the counter entrance window (the rate of increase appears to have moderated in year 14). This has resulted, first, in progressive reductions in the effective sensitivity of SSC 1 in the 5–12 keV band and, recently, to some extent in the 3–5 keV band because in the last few years the pulse heights of higher energy events are often saturated and thus unusable.

The second of the effects is present because the one-dimensional position-sensing capability of the proportional counters is based on the charge-division technique and the resistivity of carbon-coated quartz-fiber anodes. The process of event detection in the counters results in the redistribution or removal of the carbon. The resistivity of each anode thus evolves over time generally becoming larger and less uniform, and so the functions that relate charge ratio to position have changed over the course of the mission.

Third, in the last few years there is often a high background of events that have pulse heights that suggest that they are due to the detection of Al Kα photons. We do not understand in detail why this is happening but we speculate that it may be due to leakage of ultraviolet radiation through the Al-coated Kapton thermal shields that are immediately above the coded mask plates. UV radiation would produce photoelectrons at the counter body surfaces that happen to be, by design of the instrument, at potentials of approximately −1.8 kV. The photoelectrons would be accelerated toward and would hit, e.g., the aluminum collimators that are near ground potential. Some fraction of the Al Kα photons that would be produced by this process would then be detected.

Both the gain changes and charge ratio to position calibration changes are accounted for in detail in the detector model used in our coded-aperture analysis. However, the calibrations are imperfect and the derived source intensities are therefore somewhat affected by systematic errors on both short and long timescales. The coded-aperture analysis is also designed to eliminate the effects of backgrounds that are smooth and slowly varying with regard to position in the detector; this is largely but not entirely effective.

3. ANALYSIS

In X-ray astronomy, searches for periodicities where large numbers of measurements are involved have often proceeded by averaging the measured intensities in equally spaced time bins, Fourier transforming the resulting time series, producing a power spectrum (equivalently “power spectral density” or “PSD”) by taking the absolute square of the complex amplitude for each frequency, and searching for peaks in the spectrum. This process has been described in detail by, e.g., Leahy et al. (1983) and especially by van der Klis (1989). Many standard texts on Fourier analysis and its application to time series analysis also give useful background information; see, e.g., Jenkins & Watts (1968) and Percival & Walden (1993). Since our search involves $\sim 10^8$ source intensity measurements and $\sim 10^8$ trial frequencies, our analyses largely follow a conventional outline but we have implemented a few modifications as described below.

The unusual characteristics of the ASM data lead us to employ two particular strategies with the goal of improving the search sensitivity. Since the uncertainties of the individual ASM measurements in a single light curve have a wide range of values, it is advantageous to use weights such as the reciprocals of the variances when computing statistical averages. In the present instance the amplitudes in the Fourier transforms may be regarded as statistical averages, and therefore may be better determined with the use of appropriate weights. This is the first of the two strategies. The use of weights in a similar context is discussed briefly in Corbet et al. (2007a) and at greater length in Corbet et al. (2007b). These two reports also discuss the use of weights which involve the intrinsic source variability, but we do not use such weights in the work reported herein.

The second strategy stems from the fact that the observations of each source are obtained with a low duty cycle, i.e., the window function is sparse but nevertheless highly structured. The properties of the window function, in combination with the presence of slow variations of the source intensity, act to hinder the detection of variations on short timescales. The window function power spectrum has substantial power at high frequencies, e.g., 1 cycle day$^{-1}$ and 1 cycle per spacecraft orbit (~95 minute period). The Fourier transform of the data is equivalent to the convolution of a transform of a continuous set of intensity measurements with the window function transform. The high-frequency structure in the window function transform acts to spread power to low frequencies in the source intensity to high frequencies in the calculated transform (or, equivalently, the PSD). This effectively raises the noise level at high frequencies. Thus, in most of our analyses, a smoothed version of the light curve is subtracted from the binned data prior to the Fourier analysis.

An outline of the basic analysis procedure that is carried out on a dwell-by-dwell light curve is as follows.

1. The time of each intensity measurement is adjusted to the solar system barycenter.
2. The measurements are binned in equally spaced time bins using weighted averaging.
3. A smoothed version of the light curve is made using weighted averaging, a selected smoothing timescale, and either a box or Gaussian smoothing kernel.
4. The smoothed light curve is subtracted from the unsmoothed (binned) light curve to obtain a “difference light curve.”
5. A weight is applied to each bin of the difference light curve.
6. The discrete Fourier transform of the weighted difference light curve is computed, and a power spectrum is formed from the absolute values of the resulting complex Fourier amplitudes. The power spectrum is normalized so the average power is unity.
7. Maximum and average powers are obtained for sets of contiguous frequency bins.
8. “Compressed” and whitened power spectra are formed using the maximum or average powers and local (in frequency) averages of the average powers.
9. Powers in the whitened spectrum that exceed a specified threshold are listed.

This analysis procedure is described in detail in the Appendix. It was run on each source using seven different filtering timescales.

---

6 This is a function that multiplies a (hypothetical) continuous set of source intensity measurements to yield a finite set of weighted (actual) measurements, i.e., it is defined to have the value of a weight where measurements were obtained and to be zero otherwise.
and, for each of these timescales, a combination of different analysis methods and energy bands.

The powers in a spectrum of uncorrelated Gaussian white noise are expected to be well characterized by an exponential probability distribution (see, e.g., Scargle 1982; Leahy et al. 1983; van der Klis 1989; Percival & Walden 1993). The exponential nature of the distribution at any given frequency is not changed when the power is multiplied or divided by a constant. This applies to a first approximation, when power spectra are whitened. However, the averaged spectrum used as the divisor in the whitening procedure has its own probability distribution function that must be taken into account. Israel & Stella (1996) have used whitening in a search for periodicities in data that have a non-white power spectrum and have presented a thorough analysis of the effects of whitening on the probability distributions of the powers. Since the smoothed spectra used for whitening in the present search were formed from the averages of large numbers of (uncompressed) powers, we neglect the variance contributed by the smoothed spectra.

The number of independent powers that we examined must be taken into account together with the form of the distribution of each power in order to set detection thresholds. In the present case it is not immediately clear how to precisely compute the number of independent bins because (1) some of the power spectra for a given source involve the same data and differ only on account of slight variations in the analysis procedure, and (2) there is a significant degree of dependence among the powers in a spectrum because many of the bins in the light curve are empty and because of the oversampling. Although it is not justified on an a priori basis, we simply estimate the number of independent bins \( N_{\text{ind}} \) by the product of the number of frequency bins in an uncompressed spectrum that would have been obtained if the Fourier spectrum had not been oversampled, the number of energy bands analyzed (4; this neglects the non-independent bins among the four slightly different analyses of the 1.5–12 keV band), and the number of sources (571). The neglect of the oversampling factor and the multiple similar analyses of each 1.5–12 keV band light curve does not appear to have led to significant underestimates of the detection thresholds, and, thus, this procedure appears to give reasonable results.

For each value of the smoothing time parameter, a threshold \( P_{\text{thr}} \) for the detection of previously unknown periodicities was set high enough to limit the expected number of false detections \( N_{\text{exp}} \) produced by statistical fluctuations (based on the assumption that the powers are exponentially distributed). Thus, we have

\[
N_{\text{exp}} = N_{\text{ind}} e^{-P_{\text{thr}}} \quad (1)
\]

so that

\[
P_{\text{thr}} = \log N_{\text{ind}} - \log N_{\text{exp}}. \quad (2)
\]

The values of \( P_{\text{thr}} \) are given in Table 5 for \( N_{\text{exp}} = 0.1 \).

As can be seen in Figures 21 and 22, the window functions of the light curves often contain strong peaks at or close to particular frequencies. Even though the analysis procedure tends to minimize the appearance of these frequencies in the whitened power spectra, there are occurrences of peaks at these frequencies. Therefore, in each power spectrum the frequency range that we searched was limited in accordance with the binning and filtering parameters; see the values \( \nu_{\text{low}} \) and \( \nu_{\text{hi}} \) in Table 5. Furthermore, in the analyses done with filtering based on smoothing timescales of 10.0 days and under, we ignore all peaks in the frequency ranges 1.00 ± 0.04, 2.00 ± 0.04, 15.15 ± 0.20, 30.3 ± 0.2, 45.45 ± 0.20, and 60.6 ± 0.2 day\(^{-1} \).

For the other analyses, we ignore all peaks in the frequency ranges 0.00274 ± 0.00025, 0.00548 ± 0.00025, 0.01096 ± 0.00025, 0.01644 ± 0.00025, 0.01900 ± 0.00035, 0.01960 ± 0.00025, 0.02450 ± 0.00025, and 0.02500 ± 0.00025 day\(^{-1} \).

A substantial fraction of the 571 potential sources are extragalactic targets such as active galactic nuclei, extended Galactic targets such as supernova remnants, or X-ray binaries that have been in quiescence since the beginning of the RXTE mission and for which we have no expectation of finding detectable periodicities. The power spectra of these sources act effectively as controls that show representative statistics and that bring attention to periodicities that must be the product of statistical fluctuations or artifacts. Indeed, the search procedure described here was tailored in part by examination of the results on the “controls.” Furthermore, since it would be difficult to understand the reality of peaks that exceed the detection threshold in the power spectra of these sources, the effective number of sources must be less than 571. We have not adjusted the significance thresholds downward to account for this effect.

Since we searched large numbers of bins, the thresholds for the detection of previously unreported periodicities given in Table 5 are high. When a periodicity has previously been reported, it may be confirmed even if the power at or very close to the previously reported frequency is below the threshold given in the table.

Uncompressed power spectra are useful for precise estimation of the frequencies of the detected periodicities. Since the uncompressed spectra were not saved in the original analysis for smoothing timescales less than or equal to 30.0 days, the analyses that produced the most significant detection of each periodicity were repeated, if necessary, and the resulting uncompressed spectra were saved. For each periodicity a small frequency range around the major peak was fit with a Gaussian to obtain estimates of the central frequency, its uncertainty, and the peak width. The uncertainty in the frequency may be estimated based on the result of Horne & Baliunas (1986) that

\[
\delta f_1 = \frac{3}{8} \frac{1}{T \sqrt{P_r}}. \quad (3)
\]

where \( T \) is the length of the time interval covered by the light curve and \( P_r \) is the peak power in a normalized power spectrum. We also use the simple estimate

\[
\delta f_2 = \frac{1}{2T}, \quad (4)
\]

which, in most cases, should be a conservative upper limit to the uncertainty (but, if the periodicity persisted for only a fraction of the time covered by the light curve, the uncertainty could be larger than this value). In the estimates of frequencies and periods that we present below, the uncertainty derived using Equation (3) is given first and the uncertainty derived using Equation (4) is given second in square brackets.

4. RESULTS

In the present search we find clear evidence of the periodicities in GRO J1008−57 and SS 433 that have been previously detected in the ASM data but had not been detected in the analysis reported by Wen et al. (2006). Wen et al. (2006) reported the detection of the 9.56 day period of 4U 2206+543, but did not find evidence of variation with a period of ~19.1 days. Such variation was first reported by Corbet et al. (2007b). Since we
now find clear evidence of variation at the ~19.1 day period, we report its detection herein.

In the previous section, we noted that periodicities at previously identified frequencies can be found with better sensitivity than periodicities at undetermined frequencies. Therefore, we examined the power spectra for peaks at the frequencies corresponding to the periods listed in the catalogs of Bodaghee et al. (2007) and Liu et al. (2006, 2007) and thereby identified evidence of the presence of a number of periodicities that were not found by Wen et al. (2006). These are listed as detections below on the basis of the presence of a peak in the power spectrum with a power unlikely to be found in a small frequency range around the previously reported frequency (but no specific a priori threshold was set for these periodicities).

Table 1 lists the periodicities that emerge from the present search that are not listed in Tables 1–3 of Wen et al. (2006). Only one of these was, when first detected in the course of this search, previously unreported on the basis of optical or other X-ray observations, namely, the 18.545 day periodicity in IGR J18483–0311. The photon energy band, filter timescale, and method that yielded the most significant detection are given for each detected periodicity. The estimated frequencies and associated uncertainties are listed in Table 1 with the exception of the very low frequencies of the sources GRO J1008–57 and 2S 1845–024. The frequencies or, equivalently, periods of these latter sources are better obtained from epoch-folding analyses and even more precisely from pulse-timing studies.

We give in Table 2 average source intensities, peak powers seen in the whitened power spectra, and estimated average amplitudes of the detected periodic signals. The source names, photon energy bands, and periods are taken from Table 1. We give in Table 2 average source intensities, peak powers seen in the whitened power spectra, and estimated average amplitudes of the detected periodic signals. The source names, photon energy bands, and periods are taken from Table 1. The estimated average amplitudes of the detected periodic signals were obtained by superposing sine waves onto the measured intensities in the appropriate light curves and redoing the complete analysis using the appropriate method, timescale, and energy band. The sine wave frequencies were chosen to yield peaks in the power spectrum close to, but not on top of, the frequencies of the detected signals, and the amplitudes were chosen to give peak powers close to or above, within a factor of two, the peak powers of the detected signals. The results were then interpolated to estimate the amplitudes that would give rise to the peak powers of the detected signals. The uncertainty

### Notes.

- Beyond those listed in Tables 1–3 of Wen et al. (2006).
- The source name is generally that listed first by Liu et al. (2007) or Liu et al. (2006).
- See the text and Column 4 of Table 5.
- See the text and Table 4.
- Estimated from the peak centroid. The uncertainties are shown in parentheses in units of the least significant digit and were obtained from Equations (3) and (4).
- Epoch of X-ray minimum or maximum (see phase zero in each light curve shown in Figures 1 and 2).
- A peak power of 12 is seen in the second harmonic (first overtone). See Figure 11.
- A peak power of 11 is seen in the second harmonic (first overtone). See Figure 11.
- The frequency and period given are those estimated from the strongest peak in the power spectrum.
- The estimated frequencies and associated uncertainties are listed in Table 1 with the exception of the very low frequencies of the sources GRO J1008–57 and 2S 1845–024. The frequencies or, equivalently, periods of these latter sources are better obtained from epoch-folding analyses and even more precisely from pulse-timing studies.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>ASM Catalog Entry</th>
<th>Band (keV)</th>
<th>Filter Time (days)</th>
<th>Method</th>
<th>Frequency (cycles day$^{-1}$)</th>
<th>Period (days)</th>
<th>Epoch (MJD)</th>
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<tr>
<td>A 0535+26</td>
<td>x0535+26</td>
<td>1.5–12</td>
<td>500.0</td>
<td>wtgs</td>
<td>0.00906</td>
<td>110.4 ± 0.3</td>
<td>52852.57</td>
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<td>LMC X-1</td>
<td>lmc1x</td>
<td>1.5–12</td>
<td>100.0</td>
<td>wtbx</td>
<td>0.255821 (14; 100)</td>
<td>3.90898 (21; 153) d</td>
<td>52733.95 (45)</td>
</tr>
<tr>
<td>GRO J1008–57</td>
<td>groj1008–57</td>
<td>3–5</td>
<td>500.0</td>
<td>wtgs</td>
<td>0.023611 (45; 100)</td>
<td>42.35 (8; 18) d</td>
<td>52770.04 (91)</td>
</tr>
<tr>
<td>2S 1417–62</td>
<td>x1417–62</td>
<td>5–12</td>
<td>100.0</td>
<td>wtgs</td>
<td>0.111234 (11; 100)</td>
<td>8.9901 (9; 81) d</td>
<td>52742.79 (12)</td>
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<td>IGR J16320–4751</td>
<td>igri16320–4751</td>
<td>5–12</td>
<td>100.0</td>
<td>wtgs</td>
<td>0.267461 (20; 100)</td>
<td>3.73868 (28; 140) d</td>
<td>52735.84 (7)</td>
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<td>IGR J16418–4532</td>
<td>igri16418–4532</td>
<td>5–12</td>
<td>30.0</td>
<td>wtgs</td>
<td>0.102655 (19; 100)</td>
<td>9.7414 (18; 95) d</td>
<td>52738.25 (19)</td>
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<td>EXO J1722–363</td>
<td>exoj1722–363</td>
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<td>30.0</td>
<td>wtgs</td>
<td>0.218811 (16; 100)</td>
<td>4.5687 (3; 21) d</td>
<td>52736.36 (42)</td>
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<td>IGR J18027–2017</td>
<td>igri18027–2017</td>
<td>5–12</td>
<td>30.0</td>
<td>wtgs</td>
<td>0.286149 (20; 100)</td>
<td>2.9419 (28; 140) d</td>
<td>52735.84 (7)</td>
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<tr>
<td>2S 1845–024</td>
<td>x1845–024</td>
<td>5–12</td>
<td>500.0</td>
<td>wtgs</td>
<td>0.053923 (9; 100)</td>
<td>18.545 (3; 34) d</td>
<td>52754.37 (10)</td>
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<tr>
<td>IGR J18483–0311</td>
<td>igri18483–0311</td>
<td>5–12</td>
<td>100.0</td>
<td>wtgs</td>
<td>0.076452 (20; 100)</td>
<td>13.080 (3; 17) d</td>
<td>52745.19 (18)</td>
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<td>3A 1909+048</td>
<td>x1909+048</td>
<td>5–12</td>
<td>100.0</td>
<td>wtbx</td>
<td>0.104620 (13; 100)</td>
<td>9.5584 (12; 91) d</td>
<td>52740.97 (6)</td>
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<tr>
<td>4U 2206+543</td>
<td>x2206+543</td>
<td>1.5–12</td>
<td>100.0</td>
<td>wtgs</td>
<td>0.255821 (14; 100)</td>
<td>3.90898 (21; 153) d</td>
<td>52733.95 (45)</td>
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## Table 2

Characteristics of Detected Periodicities

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Band</th>
<th>Wtd. Avg. Intensitya (counts s⁻¹)</th>
<th>Unwtd. Avg. Intensityb (counts s⁻¹)</th>
<th>Approx. Period</th>
<th>Power/Thresholdc</th>
<th>Amplituded (counts s⁻¹)</th>
<th>A/f</th>
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<tr>
<td></td>
<td>1.5–12</td>
<td>0.239 (4)</td>
<td>0.084 (6)</td>
<td>216.2 h</td>
<td>23/20.3</td>
<td>0.052</td>
<td>0.22</td>
</tr>
<tr>
<td>4U 1746–536</td>
<td>1.5–12</td>
<td>2.455 (4)</td>
<td>2.291 (6)</td>
<td>3.933 h</td>
<td>22/23.7</td>
<td>0.052</td>
<td>0.021</td>
</tr>
<tr>
<td>4U 1323–62</td>
<td>1.5–12</td>
<td>0.575 (4)</td>
<td>0.449 (6)</td>
<td>2.942 h</td>
<td>27/23.7</td>
<td>0.005</td>
<td>0.096</td>
</tr>
<tr>
<td>4U 1636–536</td>
<td>1.5–12</td>
<td>9.069 (6)</td>
<td>9.339 (9)</td>
<td>3.793 h</td>
<td>22/24.1</td>
<td>0.087</td>
<td>0.0096</td>
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<tr>
<td>4U 1728–16 (GX 9+9)</td>
<td>1.5–12</td>
<td>18.879 (8)</td>
<td>19.01 (1)</td>
<td>4.193 h</td>
<td>123/24.1</td>
<td>0.283</td>
<td>0.015</td>
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<tr>
<td>4U 1746–37</td>
<td>1.5–12</td>
<td>2.275 (6)</td>
<td>2.06 (1)</td>
<td>5.163 h</td>
<td>30/23.7</td>
<td>0.004</td>
<td>0.041</td>
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<tr>
<td>GRS 1758–258</td>
<td>3–5</td>
<td>0.485 (5)</td>
<td>0.391 (7)</td>
<td>18.97 d</td>
<td>13/17.7</td>
<td>0.054</td>
<td>0.11</td>
</tr>
<tr>
<td>4U 1820–30</td>
<td>1.5–12</td>
<td>20.347 (8)</td>
<td>20.63 (1)</td>
<td>0.1903 h</td>
<td>30/24.1</td>
<td>0.12</td>
<td>0.0595</td>
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**LMXB orbital periods**

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Band</th>
<th>Wtd. Avg. Intensitya (counts s⁻¹)</th>
<th>Unwtd. Avg. Intensityb (counts s⁻¹)</th>
<th>Approx. Period</th>
<th>Power/Thresholdc</th>
<th>Amplituded (counts s⁻¹)</th>
<th>A/f</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5–12</td>
<td>0.275 (4)</td>
<td>0.550 (6)</td>
<td>110.4d</td>
<td>11/17.7</td>
<td>0.21</td>
<td>0.78</td>
</tr>
<tr>
<td>LMC X-1</td>
<td>1.5–12</td>
<td>1.524 (4)</td>
<td>1.369 (5)</td>
<td>3.909 d</td>
<td>29/18.4</td>
<td>0.064</td>
<td>0.042</td>
</tr>
<tr>
<td>GRO J1008–57</td>
<td>3–5</td>
<td>0.036 (2)</td>
<td>0.006 (3)</td>
<td>10b/17.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2S 1417–62</td>
<td>5–12</td>
<td>0.096 (3)</td>
<td>0.035 (6)</td>
<td>42.4 d</td>
<td>12/18.4</td>
<td>0.035</td>
<td>0.36</td>
</tr>
<tr>
<td>IGR J16320–4751</td>
<td>5–12</td>
<td>0.224 (4)</td>
<td>0.119 (7)</td>
<td>8.99 d</td>
<td>34/18.4</td>
<td>0.065</td>
<td>0.28</td>
</tr>
<tr>
<td>IGR J16418–4532</td>
<td>5–12</td>
<td>0.165 (5)</td>
<td>0.060 (9)</td>
<td>3.739 d</td>
<td>17/20.3</td>
<td>0.047</td>
<td>0.28</td>
</tr>
<tr>
<td>EXO 1722–363</td>
<td>5–12</td>
<td>0.132 (4)</td>
<td>0.029 (7)</td>
<td>9.741 d</td>
<td>19/20.3</td>
<td>0.051</td>
<td>0.39</td>
</tr>
<tr>
<td>IGR J18027–2016</td>
<td>5–12</td>
<td>0.189 (7)</td>
<td>0.03 (1)</td>
<td>4.569 d</td>
<td>16/20.3</td>
<td>0.009</td>
<td>0.37</td>
</tr>
<tr>
<td>2S 1845–024</td>
<td>5–12</td>
<td>0.069 (3)</td>
<td>−0.065 (7)</td>
<td>5h/17.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IGR J18483–0311</td>
<td>5–12</td>
<td>0.115 (3)</td>
<td>−0.021 (7)</td>
<td>18.54 d</td>
<td>60/18.4</td>
<td>0.099</td>
<td>0.86</td>
</tr>
<tr>
<td>3A 1909+048 (SS 433)</td>
<td>5–12</td>
<td>0.256 (3)</td>
<td>0.189 (6)</td>
<td>13.08 d</td>
<td>20/18.4</td>
<td>0.037</td>
<td>0.14</td>
</tr>
<tr>
<td>4U 2206+543</td>
<td>1.5–12</td>
<td>0.376 (4)</td>
<td>0.252 (5)</td>
<td>9.558 h</td>
<td>17/18.4</td>
<td>0.08</td>
<td>0.21</td>
</tr>
</tbody>
</table>

**HMXB orbital periods**

**Notes.**

a Weighted average of the entire ASM light curve through MJD 55196 for the energy band given in Column 2. A formal error based on the formal errors of the individual measurements is shown. For reference, the average intensities of the Crab Nebula are 75.503 (9), 26.825 (5), 23.290 (4), and 25.370 (5) counts s⁻¹ in the 1.5–12, 1.5–3, 3–5, and 5–12 keV bands, respectively. Note that the units of counts s⁻¹ are used as the general ASM proxy for source intensity and not for observed count rates, i.e., they give intensity in terms of the count rates due to the given source that would have been seen had SSC 1 been in the same physical condition as it was in 1996 March and had the source been in the center of its field of view.

b Unweighted average of the entire ASM light curve through MJD 55196 for the energy band given in Column 2. A formal error based on the formal errors of the individual measurements is shown. The unweighted average intensity is given for comparison with the weighted average; the difference is a rough indicator of the actual uncertainty in the average intensity.

c Approximate peak power in the whitened power spectrum (see the text) at the frequency given in Table 1/threshold power for the detection of the periodicity in a blind search taken from Table 5 in the Appendix.

d Amplitude of a constant-amplitude sine wave that, when superposed onto the actual data, yields a peak power close to that given in Column 6 (see the text).

ε Ratio of the inferred average signal amplitude (A; from Column 7) to the weighted average source intensity (I; from Column 3).

f, g, h See notes (g), (h), and (i) to Table 1.

i Power of the peak near half the frequency given in Table 1 or twice the period given in Column 5.

in the amplitude for a given source was estimated by the rms dispersion in the amplitudes obtained when sine waves were injected at four to ten different frequencies.

In the last column of Table 2 we give the ratio of the inferred average signal amplitude (A) to the weighted average source intensity (I). This is an indicator of the fractional variation of the source intensity at the orbital frequency. It does not include the effects of harmonics which are detected in some of the power spectra and should, therefore, be used only as a general indicator of the degree of modulation.

The ASM light curves of the sources for which we report detections of periodicities in Table 1 were folded at the listed periods. Weights were used in averaging the intensities in each phase bin. A smoothed version of the light curve was subtracted from each light curve before it was folded. The timescales used for the smoothing are listed in Table 1. After the folding was accomplished, the overall average intensity was then added to the folded light curve to show the proper mean (the mean was removed when the smoothed version was subtracted from the light curve). The folded light curves are shown in Figures 1 and 2.

The uncertainties shown in the plots of the folded light curves were determined from propagation of the 1σ uncertainties associated with each measurement in a light curve assuming the measurements are statistically independent. This neglects the effects of random source variability in at least two respects. First, the effects of source variability are not included in the formal uncertainties of the individual measurements. Second, when variability is present it almost always involves correlations from measurement to measurement.

The epochs of phase zero used in plotting the folded light curves are listed in Table 1. These epochs were determined by fitting each folded 1.5–12 keV band light curve with a combination of constant, sine, and cosine functions of phase. The epoch is then obtained from the phase of minimum or maximum intensity of the fitted function. Actual minima or maxima may deviate somewhat from these epochs; the differences may be seen in the plots of the folded light curves.

### 4.1. Additional Detections of Low-mass X-Ray Binaries

In this section, we briefly discuss our results for each of the periodicities of the LMXBs listed in Table 1. The results in
Table 1 show that, with only one exception, the most significant detections of these systems were made in the overall 1.5–12 keV energy band.

2S 0921–630 is a weak X-ray source in a low-mass system with a relatively long orbital period. Photometry of the bright optical counterpart by Chevalier & Ilovaisky (1981) and Branduardi-Raymont et al. (1981) suggested that the observed variability could be periodic, but did not yield correct estimates of the actual period. X-ray observations with the EXOSAT satellite showed intensity changes, interpreted as partial eclipses, that were key to obtaining the first relatively precise period estimate (Mason et al. 1987). Recent optical observations have also yielded relatively precise estimates of the orbital period; Shahbaz et al. (2004) obtained $P = 9.0035 \pm 0.0029$ days and Jonker et al. (2005) obtained $P = 9.006 \pm 0.007$ days. The orbital period is detected in the present study; this is shown in the power spectrum plotted in Figure 3. We derive an estimate of the orbital period of $P = 9.009 \pm 0.001 [\pm 0.008]$ days (see Table 1) that is consistent with these recently reported values. Shahbaz & Watson (2007) and Steeghs & Jonker (2007) report further work on the binary parameters including the component masses. The folded ASM light curves show that the periodic modulation has an amplitude of $\sim 30\%$ relative to the average source strength. However, the average source intensity could be affected by systematic errors in the baseline level of order 0.1 SSC counts s$^{-1}$ (1.5–12 keV band). Nonetheless, the modulation fraction must be rather large, and the periodicity may be easily detectable by other instruments.

Figure 1. ASM light curves of nine sources folded at the orbital periods and with the epochs of phase zero given in Table 1. See the text for information on the details of the folding algorithm and the error bars shown here. For each source the folded light curves are shown for two full cycles for each of the four energy bands.
4U 1254−69 is a so-called dipping LMXB. Its ∼3.9 hr orbital period was revealed in both X-ray and optical observations (Courvoisier et al. 1986; Motch et al. 1987). Díaz Trigo et al. (2009) report the results of recent observations of this source with the XMM-Newton and International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellites. They also discuss the detection of the 3.9 hr periodicity in ASM data, present a folded light curve, and use the ASM data to obtain an estimate of the orbital period of \( P = 0.16388875 \pm 0.00000017 \) days (= 3.933330 ± 0.000004 hr). We also detect the orbital period in the ASM light curves (see Figure 4) and derive a value for the period of \( P = 3.933337 \pm 0.000010 [\pm 0.000064] \) hr (see Table 1). This value is close to that of Díaz Trigo et al. (2009) but our estimate of the uncertainty is larger. We do not believe that the ASM data alone warrant a more precise estimate of the orbital period than we have given.

4U 1323−62 is also a dipping LMXB. Parmar et al. (1989a) report on EXOSAT X-ray observations wherein the orbital period of the binary system was manifest in terms of intensity dips that recurred with a period of \( P = 2.932 \pm 0.005 \) hr. Later, Balucinska-Church et al. (1999) derived a period of \( P = 2.938 \pm 0.020 \) hr from X-ray observations with BeppoSAX. Even though the source is rather weak, the orbital period is easily detected in the ASM light curves (see Figure 5). We derive a value for the period of \( P = 2.941923 \pm 0.000005 [\pm 0.000036] \) hr (see Table 1). It is interesting to compare this value with the conclusion of Parmar et al. (1989a) that consideration of the times of dips in two observations separated by one year imply that the period must be more precisely given by

Levine et al.

Figure 3. Top: portion of a compressed power spectrum made from the 1.5–12 keV light curve of 2S 0921−630. The “wtbx” method and a 30.0 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the corresponding uncompressed PSD.

Figure 4. Top: portion of a compressed power spectrum made from the 1.5–12 keV light curve of 4U 1254−69. The “wtgs-v4” method and a 3.0 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the corresponding uncompressed PSD.

\[ P = 2.932128 \pm 0.000002 \pm n \times 0.000977 \text{ hr}. \] The ambiguity in this formula reflects an ambiguity in the number of orbital cycles in the one-year interval between the observations. The present determination of the orbital period implies \( n = 10 \) and that \( P = 2.941898 \pm 0.000005 \text{ hr} \) where the uncertainty is dominated by the uncertainty of the correction for \( n = 10 \). Given that the difference between this period and the ASM-derived value is only \( \Delta P = 0.000025 \text{ hr} \) and considering the uncertainties in the two measurements, we conclude that the two values are mutually consistent. Recent studies of this source may be found in Bałucińska-Church et al. (2009) and Balman (2009).

4U 1636−536 is a persistent LMXB that often displays Type I X-ray bursts. The orbital period was found through optical photometry (Pedersen et al. 1981). It is also evident through radial velocity measurements made from emission line profiles obtained in optical spectroscopic observations (e.g., Augusteijn et al. 1998; Casares et al. 2006). Estimates of the orbital period have been successively improved by van Paradijs et al. (1990), Augusteijn et al. (1998), and Giles et al. (2002) since the discovery by Pedersen et al. (1981). To our knowledge, the best optical ephemeris is that of Giles et al. (2002), who estimate that the period is \( P = 3.7931263 \pm 0.0000038 \text{ hr} \). The ASM detection (see Figure 6) is secure, given knowledge of the optical period, but would not be sufficiently strong to have been detected in our blind search. It is, nonetheless, the first detection of the orbital period in X-rays. The period estimated from the ASM results is \( P = 3.793128 \pm 0.000008 \pm 0.000060 \text{ hr} \) (Table 1). This value is consistent with that of Giles et al. (2002) though it is somewhat less precise.

4U 1728−16 (GX 9+9) is a rather bright persistent LMXB. The orbital periodicity at the period of \( P = 4.19 \text{ hr} \) was found in HEAO 1 A-1 X-ray data by Hertz & Wood (1988). Soon afterward, Schaefer (1990) found variations at essentially the same period in the brightness of the optical counterpart. The ASM detection and an account of the variability in the ASM data of the modulation amplitude is described in full by Harris et al. (2009). The periodicity is manifest with even greater significance in the longer data set used in our most recent analyses; compare Figure 7 with Figure 2 of Harris et al. (2009). In Table 1 we also give an updated estimate of the orbital period that is only slightly different from that given by Harris et al. (2009).
Figure 6. Top: portion of a compressed power spectrum made from the 1.5–12 keV light curve of 4U 1636−536. The “wtgs” method and a 0.9 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the corresponding uncompressed PSD.

Figure 7. Top: portion of a compressed power spectrum made from the 1.5–12 keV light curve of GX 9+9. The “wtgs” method and a 0.9 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the corresponding uncompressed PSD.

4U 1746−37 is an LMXB in the globular cluster NGC 6441. X-ray observations carried out with EXOSAT, Ginga, and RXTE/Proportional Counter Array (PCA) showed the presence of dips that occur roughly every 5 hr and quickly led to the interpretation that their recurrence period is the orbital period (Parmar et al. 1989b; Sansom et al. 1993; Balucińska-Church et al. 2004). The current best estimate of the orbital period, \( P = 5.16 \pm 0.01 \) hr, was given by Balucińska-Church et al. (2004). This periodicity is seen with high significance in the ASM data (see Figure 8). We obtain the period estimate \( P = 5.163287 \pm 0.000018 \pm 0.000111 \) hr that is consistent with the results of Balucińska-Church et al. (2004) but is substantially more precise.

GRS 1758−258 most likely comprises a black hole accreting from a K-type giant star (Smith et al. 2002; Rothstein et al. 2002, and references therein). Smith et al. (2002) found a periodicity with \( P = 18.45 \pm 0.01 \) days in the data obtained in extensive RXTE PCA observations done in the years 1997 through 2000 and interpreted the period as the orbital period. Rothstein et al. (2002) performed near-IR observations and identified an early K-type star as the likely companion if the orbital period is as long as 18.45 days. We find a peak in the ASM power spectrum shown in Figure 9 that corresponds to a period of \( P = 18.973 \pm 0.007 \pm 0.036 \) days and that we therefore identify with the orbital period.

4U 1820−30 is a very bright LMXB in the globular cluster NGC 6624. Stella et al. (1987) analyzed data from X-ray observations with EXOSAT and discovered the 11 minute orbital period. The periodicity is only evident as a 3% or less peak-to-peak modulation in the overall X-ray intensity. Chou & Grindlay (2001) used measurements made by a number of X-ray satellites of the times of maxima of the 11 m variation to obtain an ephemeris wherein both linear and quadratic terms are significant. To our knowledge, this is the most precise ephemeris in the literature at this time. We detect the periodicity in the ASM light curve with high significance; see Figure 10 and Table 1. The period we obtain, \( P = 685.01092 \pm 0.00007 \pm 0.00054 \) s, is an average over the duration of the ASM data set and effectively applies near the mid-time of this interval, i.e., near MJD 52620. We can compare our period measurement with the period of \( P = 685.01126 \) s predicted for this epoch by the Chou & Grindlay (2001) ephemeris. If we assume that the smaller of the two uncertainties in the ASM period that are given in Table 1 is applicable, then the ASM period is about
Figure 9. Top: power spectrum made from the 3–5 keV light curve of GRS 1758–258. The “wtgs” method and a 500.0 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the uncompressed PSD.

Figure 10. Top: portion of a compressed power spectrum made from the 1.5–12 keV light curve of 4U 1820–30. The “wtgs” method and a 0.9 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the corresponding uncompressed PSD.

Figure 11. Power spectra made using the “wtgs” method and a 500.0 day smoothing timescale. Only the low-frequency regions of the power spectra are shown. Top: power spectrum made from the 1.5–12 keV light curve of A 0535+26. The “ringing” appearance derives from a light curve where a small number of strong outbursts punctuate an otherwise low source strength. Middle: power spectrum made from the 3–5 keV light curve of GRO J1008–57. Bottom: power spectrum made from the 5–12 keV light curve of 2S 1845–024. The previously determined orbital frequencies are 0.009066 (25) day$^{-1}$ (A 0535+26), 0.004018 (8) day$^{-1}$ (GRO J1008–57), and 0.0041292 (2) day$^{-1}$ (2S 1845–024).

4.2. Additional Detections of High-mass X-Ray Binaries

The orbital periods of a number of HMXBs are listed in Table 1. In contrast with the results on LMXBs, Table 1 shows that the majority of the most significant detections of these systems were made in the 5–12 keV energy band. This is not unexpected since many of the accreting compact objects in HMXBs are X-ray pulsars that tend to have relatively hard X-ray spectra.

A 0535+26 is a Be/X-ray pulsar that can be rather bright in X-rays during transient outbursts. The early observations are reviewed by Finger et al. (1996b). Pulse-timing analyses of observations obtained with the BATSE instrument on the Compton Gamma-Ray Observatory were used to determine that the orbital period is $P = 110.3 \pm 0.3$ days (Finger et al. 1996b, and references therein). A portion of an ASM power spectrum is shown in Figure 11. This figure demonstrates that the periodicity is apparent, but is not detected with sufficient significance to allow us to obtain a useful improvement in the precision of the orbital period. Seven separate peaks in the intensity of this source are apparent in the latter part of the ASM light curve. Their average separation is close to 114 days and is probably not consistent with the period determined through pulse timing. The outbursts of some other Be star/neutron star binaries do not occur at precisely the orbital periods determined by pulse timing, so there is no reason in this case to doubt the accuracy of the pulse-timing value.

LMC X-1 is a luminous HMXB in the Large Magellanic Cloud which highly likely comprises a stellar-mass black hole and its normal OB-type companion. The properties of the system are described in detail by Orosz et al. (2009). Orosz
et al. (2009) also present the ASM results and how they relate to other observations including other period determinations. Orosz et al. (2009) adopt the value of $3.90917 \pm 0.00005$ days as their best estimate of the period based on optical photometry and spectroscopy. An updated ASM power spectrum is shown in Figure 12 and revised estimates, based solely on the ASM power spectrum, of the orbital frequency and period are given in Table 1. We note that the ASM detection provides the only reported evidence to date of the orbital period in X-rays and that our X-ray-based period estimate of $P = 3.90898 \pm 0.00021 [\pm 0.00153]$ days is fully consistent with the optically based value of Orosz et al. (2009).

**GRO J1008−57** is a transient X-ray pulsar in a Be/X-ray binary discovered with the BATSE experiment (see references in Shrader et al. 1999; Coe et al. 2007). Shrader et al. (1999) used ~2 years of ASM data to obtain an early estimate of the outburst period of $P \sim 135$ days. Levine & Corbet (2006) reported a relatively precise determination of the outburst period, $P_{\text{outburst}} = 248.9 \pm 0.5$ days, that was based on the time intervals between widely spaced outbursts. We believe that this is still the best current estimate of the outburst cycle time. The ASM power spectrum is shown in Figure 11. Though the peaks due to the outburst periodicity are clear, they are not sufficiently well defined to yield a superior period estimate. Coe et al. (2007) have estimated the orbital period through timing of the $93$ s pulsations seen in the BATSE data. They obtained the result $P = 247.8 \pm 0.4$ days and noted that it is in good agreement with the result of Levine & Corbet (2006).

**2S 1417−62** is also a transient pulsar in a Be/X-ray binary system. A brief description of the early history and of a pulse-timing analysis using BATSE data may be found in Finger et al. (1996a). The BATSE timing analysis yielded an estimate of the orbital period of $P = 42.12 \pm 0.03$ days as well as the projected semimajor axis, eccentricity, epoch of periastron passage, and other orbital elements. A slight revision to the orbital period and time of periastron passage have been given by Inam et al. (2004). Evidence of outbursts recurring at intervals that are close in duration to the orbital period (or multiples thereof) is seen in the ASM power spectrum (see Figure 13). Frequency and period estimates obtained from the spectrum shown in Figure 13 are listed in Table 1 but are not as precise as the pulse-timing values.

**IGR J16418−4532** is an X-ray source in the Galactic plane that was discovered using INTEGRAL (Tomsick et al. 2004). Corbet et al. (2006) found and measured the orbital period using both Swift/BAT and ASM data and obtained the values $3.753 \pm 0.004$ days and $3.7389 \pm 0.0004$ days, respectively. Our current ASM power spectrum (Figure 15) shows a peak that is moderately significant given prior knowledge of the period. The frequency of this peak corresponds to the period $P = 3.73886 \pm 0.00028 [\pm 0.00140]$ days. This period is essentially identical to that determined earlier from the ASM data by Corbet et al. (2006).

**EXO 1722−363** is an X-ray pulsar in a high-mass binary system seen edge-on (Thompson et al. 2007 and references therein). Eclipses were found in X-ray observations made in scans of the Galactic plane with the RXTE PCA and their temporal spacing was used to get the first real measurement of the orbital period, i.e., $P = 9.741 \pm 0.004$ days (Corbet et al. 2005). Thompson et al. (2007) have estimated the orbital parameters through a pulse-timing analysis and obtain a value...
for the period of $P = 9.7403 \pm 0.0004$ days. One might expect a strong signal from an eclipsing system but the source intensity is rather modest, about 4 mCrab (1.5–12 keV) on average in the ASM observations. Thus, only a modest peak is evident close to the frequency in the ASM power spectrum (see Figure 16). We estimate the period to be $P = 9.7414 \pm 0.0018$ [±0.0095] days. This is consistent with but somewhat less precise than the pulse-timing-based estimate of Thompson et al. (2007). Mason et al. (2010) have recently reported estimates of the masses of the two components of the binary system and confirm that it is indeed an HMXB.

SAX J1802.7–2017 = IGR J18027–2016 is only ∼22 away from the bright X-ray source GX 9+1. It was discovered using BeppoSAX and, despite its proximity to a much brighter source, was found to be an X-ray pulsar in an HMXB system (Augello et al. 2003). Changes in the apparent pulse period led Augello et al. (2003) to infer that the pulsar is in an orbit with a period of ∼4.6 days. Hill et al. (2005) realized that the INTEGRAL source IGR J18027–2016 is associated with the SAX source and refined the orbital period to be $P = 4.5696 \pm 0.0009$ days. Jain et al. (2009) used Swift/BAT, INTEGRAL-ISGRI, and RXTE-ASM data to estimate that the orbital period is $P = 4.5693 \pm 0.0004$ days. This periodicity is apparent in our ASM power spectra (see Figure 17). We use the present results to estimate $P = 4.5687 \pm 0.0003$ [±0.0021] days.

2S 1845–024 = GS 1843–02 is an accreting pulsar that is evident during widely spaced outbursts (Finger et al. 1999, and references therein). A fairly precise value for the orbital period of $P = 242.18 \pm 0.01$ days was determined by Finger et al. (1999) by a pulse-timing analysis of BATSE data. A small number, ∼5, of outbursts are evident in the mission-long ASM light curve, and the outburst periodicity is weakly evident in the ASM power spectrum (see the lower panel of Figure 11). However, the ASM results do not support a determination of an orbital period that can approach the precision of the pulse-timing-based value determined by Finger et al. (1999). Hence, we do not present an ASM-based estimate of the period.

IGR J18483–0311 was discovered in INTEGRAL/IBIS observations of the Galactic center region (Chernyakova et al. 2003). The orbital period was independently found around the same time by Levine & Corbet (2006) in the ASM light curve and by Sguera et al. (2007) in the INTEGRAL light curve. The reported values for the period were 18.55 ± 0.03 days and 18.52 ± 0.01 days, respectively. Jain et al. (2009) have recently analyzed Swift/BAT and ASM data and estimate the
period to be $P = 18.5482 \pm 0.0088$ days. The period is detected with high significance in the present study (see Figure 18). We use that power spectrum to estimate that the orbital period is $P = 18.545 \pm 0.003 \pm 0.034$ days.

**3A 1909+048** is the X-ray counterpart to the well-known object **SS 433**. This object most likely consists of a stellar-mass black hole that is accreting at super-Eddington rates from a strong wind emitted by a high-mass normal-type star, and produces jets wherein the outflow velocity is approximately 0.26$c$. An early review may be found in Margon (1984) and a more recent one in Fabrika (2004). The precession of the jets with a period of $\sim 162$ days is not only evident in the moving optical lines, but also in other phenomena including the apparent X-ray intensity (see Wen et al. 2006; Gies et al. 2002). A number of reports discuss the evidence from optical spectroscopy for Doppler shifts of the compact and nondegenerate components and their interpretation in terms of orbital parameters and component masses (see, e.g., Hillwig & Gies 2008; Cherepashchuk et al. 2009; Kubota et al. 2010). Goranskii et al. (1998) reported a precise measurement of the orbital period of the binary, i.e., $P_{\text{orb}} = 13.08211 \pm 0.00008$ days, on the basis of the times of eclipse-like dips in the optical flux. The X-ray intensity also shows eclipse-like dips (e.g., Filippova et al. 2006; Cherepashchuk et al. 2009) but these have not yet been exploited for orbital period estimation. Gies et al. (2002) reported the first evidence of the orbital period in the ASM X-ray intensity measurements. Very recently, Kubota et al. (2010) obtained a new time of minimum optical brightness and used it, together with the earlier observations, to obtain a revised value of the period, $P_{\text{orb}} = 13.08227 \pm 0.00008$ days. In the present analysis, we find unambiguous evidence of both the precession and the orbital periods in the power spectrum (see Figure 19). Our estimate of the orbital period is $P_{\text{orb}} = 13.080 \pm 0.003 \pm 0.017$ days. This value is consistent with, but somewhat less precise than, those of Goranskii et al. (1998) and Kubota et al. (2010). If we fold the ASM light curve with the period and epoch of Kubota et al. (2010), we find that the time of X-ray minimum is coincident with the time of optical minimum. The shape of the folded ASM light curve is similar to the eclipse-like shapes seen by INTEGRAL (e.g., Cherepashchuk et al. 2009) and suggests that the eclipse-like decrease in the flux is the result of periodically occurring partial occultations of the X-ray emitting regions, broadly construed.

**Figure 17.** Top: portion of a compressed power spectrum made from the 5–12 keV light curve of IGR J18027$–2016$. The “wtgs” method and a 30.0 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the corresponding uncompressed PSD.

**Figure 18.** Top: portion of a compressed power spectrum made from the 5–12 keV light curve of IGR J18483$–0311$. The “wtgs” method and a 100.0 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the corresponding uncompressed PSD.

**Figure 19.** Top: portion of a compressed power spectrum made from the 5–12 keV light curve of SS 433. The “wtgs” method and a 100.0 day smoothing timescale were employed in producing the PSD. Bottom: a small region of the corresponding uncompressed PSD.
to include regions where the X-ray flux may be scattered (see Figure 2).

4U 2206+543 is an HMXB which manifests a distinct variation at a period of \( P \approx 9.6 \) days in the ASM light curve (Corbet & Pele 2001). This source is included in this report even though the \( \sim 9.6 \) day period was reported by Wen et al. (2006) because the underlying period may actually be twice as long, or \( \sim 19.2 \) days (Corbet et al. 2007b; see also Wang 2009). In this regard, Corbet et al. (2007b) found a signal at a period of \( P = 19.25 \pm 0.08 \) days in Swift/BAT data and a signal near the same period in ASM data. Wang (2009) found a peak near a period \( P = 19.11 \) days in the ASM data. Our power spectrum of ASM data also shows peaks at frequencies corresponding to both periods (see Figure 20). The more significant peak corresponds to a period of \( P = 9.5584 \pm 0.0012 [\pm 0.0091] \) days. Assuming that the subharmonic corresponds to a period twice this value, we obtain \( P = 19.117 \pm 0.003 [\pm 0.018] \) days. Radial velocity measurements from optical or near-IR spectroscopy are needed to unambiguously determine the true orbital period.

4.3. Nondetections and Search Sensitivity

The estimates of the amplitudes of the periodic signals that are reported in Table 2 fall, in many of the cases, just below the detection thresholds of the present blind search. They thereby illustrate the typical sensitivity of the present search. We have also estimated the amplitudes that approximately correspond to our detection thresholds in a set of additional sources chosen either to help cover a wide range of intensities or because they are of interest for other reasons. To accomplish this we have computationally superimposed sine waves onto the ASM light curves and repeated the search analyses on the light curves for those particular sources in order to determine the signal amplitudes that would have resulted in peaks reaching powers of \( \sim 25 \) in the whitened power spectra. These estimates, which may be taken as upper limits since we would have recognized peaks near these frequencies that reached powers as small as 15, are listed in Table 3. This table also lists previously reported periods for some of the sources as well as mission-average intensities. Column 7 of the table gives the effective upper limits on the amplitudes as fractions of the average source intensities.

Levine & Corbet (2006) reported modest significance detections of periodicities in ASM power spectra for GRO J1655−40, GX 339−4, V4641 Sgr, and 4U 1957+115 at or very close to the periods previously reported in the literature. In the analyses using the entire ASM light curves that we have done recently we do not confirm these possible detections. Results of sensitivity analyses for these sources are included in Table 3.

Table 3 also includes entries for two bright sources, Sco X-1 and 4U 1735−444, with well-established periodicities that we do not detect as well as entries for three sources, i.e., the Crab Nebula, GX 340+0, and GX 5−1, that do not have known orbital periodicities. Table 3 gives upper limits, calculated as described above, on any modulation near the reported periods. We note that for Sco X-1 the noise is dominated by the intrinsic source variations. In rare cases, such as that described by Vanderlinde et al. (2003), specialized techniques may be available to partially mitigate the effects of the intrinsic variation and improve the sensitivity of a periodicity search. We have not tried to apply any such techniques in the present general search. The upper limits on periodicities in the power spectra for the Crab, GX 340+0, and GX 5−1 are included in this table to illustrate the typical sensitivity of the present search in the cases of bright sources.

We also did not detect the alias of the 290 s pulse period in X1145−619 that was reported in Levine & Corbet (2006). This is not that unexpected since pulse periods tend to change more rapidly than orbital periods and could change to a degree that makes them significantly noncoherent and therefore hard to detect in a 14 year data set.

In short, Tables 2 and 3 show that the search sensitivity depends on a number of factors including source strength, degree of intrinsic source variability, and quality of the ASM light curve (which, in turn depends on the source location relative to nearby bright sources, etc.).

5. DISCUSSION

The present search for periodicities in the ASM light curves has proved to be more sensitive than the earlier search done by Wen et al. (2006). The weighting and filtering aspects of our search algorithms are major factors in the sensitivity improvements. Another major factor is the use of light curves that cover \( \sim 5 \) more years. The result is the detection of the orbital periods in 8 LMXBs and in \( \sim 12 \) HMXBs that were not detected by Wen et al. (2006). For each of these systems, the orbital periods, epochs, signal amplitudes, and modulation fractions are given in Tables 1 and 2, and folded light curves are given in Figures 1 and 2. Our detection of the 18.545 day period of IGR J18483−0311 represents the co-discovery with Sguera et al. (2007) of the orbital period of this system. Our detections of the orbital periods of 4U 1636−536 and LMC X-1 are the first for these systems, to our knowledge, that have been accomplished on the basis of X-ray observations. The present measurements of the orbital periods of 2S 0921−630, 4U 1323−62, 4U 1746−37, GRS 1758−258, IGR J16320−4751, IGR J18483−0311, and 4U 2206+543 are the most precise values reported to date to our knowledge.

In addition to the sensitivities achieved, the present search is comprehensive in terms of sources studied and frequency range covered. Even though some of these results have been reported previously by us (see the paragraphs above on individual
systems), the tables presented herein and the folded light curves, together with the periodicity tables and light curve figures in Wen et al., are a compact source of information on orbital and other periodicities in the ∼200 brightest X-ray binaries. The results present a starting point for future searches for long-term periodicities in, e.g., the X-ray binaries where the orbital period is presently unknown.

It is interesting to compare the present list of detections together with those of Wen et al. (2006) with Tables 1.1 and 1.3 of White et al. (1995) that list the well-established orbital periods of LMXBs and HMXBs as of 1994 or 1995. Table 1.1 of White et al. (1995) lists 32 LMXBs with known orbital periods. Of these, seven have been in quiescence through the entire RXTE mission and one (CAL 87) is a supersoft source that emits at energies below the ASM band; these systems would not be expected to yield periodicity detections in ASM data. The periodicities of 17 of the remaining 24 systems have now been detected in the ASM light curves if we include Sco X-1 per the results of Vanderlinde et al. (2003) even though its orbital period was not detected in the present study. Seven systems that are detected by the ASM by virtue of their intensities do not yield periodic detections in the present search. The ASM periodicity searches have yielded clear detections of the orbital periods of 13 of the 16 systems listed in Table 1.1 of White et al. (1995) that had, at that time, shown evidence of the orbital period in X-rays (see Column 5 therein). Two of the remaining three systems have been in quiescence throughout the RXTE mission. The last remaining system is Cyg X-2 for which we find no evidence of the 9.8 day period even though it is rather bright in X-rays.

Table 1.3 of White et al. (1995) lists 24 HMXBs with known orbital periods. Of these, only one (X0535−668) has been in quiescence during the entire RXTE mission. The orbital periodicities of 16 of the remaining 23 systems have been clearly detected in power spectra of the ASM light curves; we do not count X0535+262 as a clear detection in the power spectrum. The periods of four of the systems (X0115+634, X0535+262, GX 304−1, and X1145−619) are apparent in the ASM light curves as limited sequences of short transient outbursts that are separated by the orbital period or small multiples thereof. The HMXBs X1553−542 and X0331+530 are evident in the ASM light curves during short transient outbursts, but the ASM yields no evidence of their orbital periods. We also find no evidence of the 1.7 day period of LMC X-3 even though the source was detectable over most of the 14 year interval used in the present analysis.

Not unexpectedly, we find that the amplitudes of the variations at the orbital period, when expressed as fractions of the average intensity, are typically low for LMXBs and high for HMXBs (see Tables 2 and 3). This is consistent with the relatively low rate of detections of orbital modulation in LMXBs and the high rate in HMXBs. There are some exceptions such as the high fractional modulation of the weak LMXB 2S 0921−630 and the low degree of modulation of the HMXBs LMC X-1 and LMC X-3. Our results for 2S 0921−630 suggest that there could be other weak LMXBs with fractional amplitudes that are not particularly low and that would not be difficult to detect with an instrument somewhat more sensitive than the ASM. Indeed, it is likely that the Monitor of All-Sky X-ray Image (MAXI) instrument on the International Space Station (Matsuoka et al. 2009) will produce light curves useful for extending the search for periodicities in X-ray light curves and will be able to find many additional periodicities and orbital periods.

We gratefully acknowledge the efforts of the RXTE/ASM science teams at MIT and NASA/GSFC, and the RXTE mission support groups at GSFC. We thank Alex Camacho for computing the upper limits presented in Table 3. We also want to acknowledge an anonymous referee for helpful comments. This work was supported by NASA through Contract NAS 5-30612 (MIT).

### APPENDIX

### DETAILS OF THE ANALYSIS PROCEDURE

The details of the procedure used in the present periodicity search is described below. An ASM light curve file consists of a large number of rows, where each row comprises the
start time of an observation, a source intensity, an estimate of the uncertainty in the source intensity, and ancillary data. First, the time of each intensity measurement was adjusted to approximately remove the effects of the motion of the Earth around the solar system barycenter, and the adjusted times were used to assign the measurements to equally spaced time bins of duration 5 minutes (0.0034722 days) or more. Weights are used in averaging those measurements that fall into a given time bin. The $n_i$ measurements that fall into time bin $i$ are distinguished by the index $j$ that runs from 1 to $n_i$. We denote the $j$th measured source intensity in a time bin by $s_j$ and its associated $1\sigma$ uncertainty by $\sigma_j$. The averaging in this stage uses weights $w_j = 1/\sigma_j^2$, where $k_A$ is a selected weighting index (see values in Table 4). The weighted average intensity in bin $i$ is then

$$d_i = \frac{\sum_{j=1}^{n_i} s_j / \sigma_j^{k_A}}{\sum_{j=1}^{n_i} 1/\sigma_j^{k_A}}. \quad (A1)$$

For convenience we denote the denominator of this expression by $W_i$ so that

$$W_i = \sum_{j=1}^{n_i} 1/\sigma_j^{k_A}. \quad (A2)$$

The $W_i$ are used to weight the time bins in the subsequent analysis. It should be understood that $d_i = 0$ and $W_i = 0$ for those time bins that contain no measurements.

As stated above, a smoothed version of the light curve is, in many of our analyses, subtracted from the binned data. The smoothed version is given by a time bin by time bin ratio in which the numerator is computed by convolving a kernel function with a weighted version of the binned light curve. The denominator is computed by convolving the same kernel function with an identically weighted version of the window function. The value of the $i$th bin of the smoothed data is given by

$$D_i = \frac{(K \otimes (W \cdot d))_i}{(K \otimes W)_i}, \quad (A3)$$

where $K$ represents the kernel function, $d$ and $W$ are the above defined data and weighting functions of the time bin index $i$, and “$\otimes$” denotes convolution. The kernel function $K$ may be either a Gaussian or a box function. In the case of the Gaussian kernel, the FWHM response is taken to be equal to the smoothing time parameter. The Gaussian is calculated out to $\pm 14$ standard deviations from its center. In the case of the box function, the box width is taken to be twice the smoothing time parameter. The convolution is accomplished using Fourier transforms.

We repeated the analyses using seven different values of the smoothing time parameter (see Table 5) to optimize the sensitivity in each of several different frequency ranges. In each case the smoothed light curve was subtracted from the unsmoothed light curve, weights were applied, and the results were Fourier transformed. In symbols, this part of the analysis produces a filtered light curve described by

$$F_i = Y_i (d_i - D_i), \quad (A4)$$

where the weights $Y_i$ are given by

$$Y_i = W_i^{k_B/k_A} = \left[ \sum_{j=1}^{n_i} 1/\sigma_j^{k_A} \right]^{k_A/k_B} \quad (A5)$$

and $k_B$ is a second weighting index. Weight index values are given in Table 4. The weights used in the “wt,” “wtgs,” and “wtbx” analysis versions are the inverses of the variances obtained from propagating the uncertainties on the intensities given in the light curve files. The other analysis versions used variations of the weights. These different weighting schemes were used because the nature of the noise, made up of contributions from photon-counting statistics, intrinsic source variability, and systematic measurement errors, is somewhat different in each source and each energy band. In two analysis versions, there was no subtraction of a smoothed version of the light curve.

The unweighted average of the $F_i$ which correspond to bins with nonzero exposure is computed and then subtracted from each of the $F_i$ values for those bins. The resultant array is extended with zeroes by a factor of four and Fourier transformed. The extension of the array yields oversampling in the frequency domain. The oversampled transform is converted into a power spectrum which is normalized to have an average value of unity.

The normalized power spectra are compressed by saving the average and maximum values for sets of contiguous frequency bins; the number of contiguous bins ($N_{\text{bins}}$) depends on the frequency range and smoothing time parameter (see Table 5). The compression was done to facilitate plotting of power spectra for inspection and presentation purposes and to reduce the amount of disk space needed to store the result files, but it also turned out to be useful in whitening the spectra as described below.

We found that for the analyses where short smoothing timescales were used, i.e., timescales of 0.3, 0.9, and 3.0 days, the compressed power spectra have a non-white appearance. The effect is strongest for the shortest smoothing timescale, i.e., 0.3 days. It is not clear how to apply a threshold for detection of a periodicity in a non-white spectrum. Therefore, we added a procedure (to the code that performs the compression described above) to compute a “background” average power around each compressed frequency bin, and to then obtain whitened maximum values (cf. Israel & Stella 1996). To be specific, the average power for a particular compressed frequency bin is obtained from the average of the powers in $N_{\text{space}}$ compressed bins on each side of the given compressed bin. The bins used in computing the average have a minimum spacing from the given bin of $N_{\text{space}}$ compressed bins. In practice,

\[ N_{\text{space}} \text{ is set to 1 for those smoothing timescales where compression was done on the spectra, and to 3 when the spectra were not compressed because a periodicity may produce a feature that is wider than one frequency bin.} \]

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Figure 21. Power spectra (PSDs) based on the 1.5–12 keV ASM light curve of LMC X-2. These PSDs were made using a smoothing timescale of 0.3 days and have been compressed using the standard parameters (Table 5); they illustrate the compression and whitening procedure used in the search (see the text). The Nyquist frequency is 144 day\(^{-1}\). (a) PSD of the window function, i.e., of the weights used in the analysis of the data. For this example the weights are the reciprocals of the formally estimated variances of the binned data. Time bins of the window function which do not contain any measurements are assigned weights of zero. Prominent peaks are seen at frequencies of 1 day\(^{-1}\) and \(\sim 15\) day\(^{-1}\), i.e., the orbital frequency of the RXTE spacecraft, and harmonics thereof. The strong peaks seen close to zero frequency and to 1 day\(^{-1}\) reach, respectively, to powers of 350 and 550 in terms of the units in this panel. (b) The maximum values of each set of 300 contiguous bins of the light curve PSD. (c) The average values of each set of 300 contiguous bins of the light curve PSD. (d) The whitened maximum values of the PSD consisting of the maximum values shown in (b) divided by a local (in frequency) background determined from (c). In this example, no power is seen that exceeds the detection threshold.

Table 5
Filtering Timescales and Parameters

<table>
<thead>
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<th>Timescale (days)</th>
<th>Bin Time (days)</th>
<th>(N_{\text{rebin}})</th>
<th>(N_{\text{avg}})</th>
<th>(N_{\text{space}})</th>
<th>(v_{\text{low}}) (day(^{-1}))</th>
<th>(v_{\text{hi}}) (day(^{-1}))</th>
<th>Threshold Power</th>
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<td>3</td>
<td>0.0007</td>
<td>1.0</td>
<td>17.7</td>
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<tr>
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<td>300</td>
<td>3</td>
<td>0.004</td>
<td>1.0</td>
<td>17.7</td>
</tr>
<tr>
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<td>1.0</td>
<td>1</td>
<td>300</td>
<td>3</td>
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<td>1.0</td>
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<td>1</td>
<td>0.1</td>
<td>4.0</td>
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</tr>
<tr>
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<td>0.2</td>
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</tr>
<tr>
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<td>1</td>
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<td>2.2</td>
<td>144.0</td>
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<tr>
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<td>0.0034722222</td>
<td>300</td>
<td>6</td>
<td>1</td>
<td>6.6</td>
<td>144.0</td>
<td>24.1</td>
</tr>
</tbody>
</table>

Notes.

\(^{a}\) The timescale characterizes the width of the smoothing kernel used in filtering. The bin time is the duration of the time bins used in the analysis.

\(^{b}\) Average and maximum powers in “compressed” frequency bins are obtained from sets of \(N_{\text{rebin}}\) contiguous frequency bins in the original PDS. For use in whitening each compressed frequency bin, a background average power is obtained from \(N_{\text{avg}}\) of these compressed bins on either side of, and at least \(N_{\text{space}}\) compressed bins away from, the particular compressed frequency bin.

\(^{c}\) Low \((v_{\text{low}})\) and high \((v_{\text{hi}})\) ends of the frequency range searched.

\(^{d}\) Power, in units of the local average power, needed for a detection in the blind search.

Table 4 lists, at the highest level, the variations of the analysis method that we have used. We found that the results from the methods where both weighting and filtering were applied (“wtgs,” “wtgs-v4,” “wtgs-v8,” and “wtbx”) were almost always nearly equal or superior to the results obtained with the other methods (“unwt,” “wt,” “ungs”). A typical, i.e., not the extreme best case, of the differences is illustrated in Figure 22. Therefore, we did not search for significant peaks in the power spectra obtained using the latter methods. The “wtgs,” “wtgs-v4,” “wtgs-v8,” and “wtbx” methods were all applied to the 1.5–12 keV band light curves, but the results generally produced power spectra that were quite similar in terms of both detailed appearance and sensitivity. Therefore, only the “wtgs” method was applied to the other three energy bands. The results from the four energy bands are, in some cases, quite different.
Figure 22. Power spectra (PSDs) based on the 1.5–12 keV ASM light curve of X1323−619 that illustrate the typical differences in the results obtained over a representative set of variations of the analysis algorithm. The PSDs in panels (b)–(e) have been compressed using the standard parameters for the 3.0 day smoothing timescale (see Table 5); the whitened maximum powers are shown here. The Nyquist frequency is 100 day$^{-1}$, but only frequencies up to 40 day$^{-1}$ are shown. (a) PSD of the window function; see the caption for Figure 21. (b) PSD computed with intensities that are neither weighted nor filtered by subtraction of a smoothed version of the light curve ("unwt" entry in Table 4). (c) PSD computed with intensities that are weighted but are not filtered ("wt" in Table 4). (d) PSD computed with intensities that are not weighted but are filtered ("ungs" in Table 4). The light curve was smoothed using a 3.0 day timescale for use in the filtering for the PSDs shown in this panel and in panel (e). (e) PSD computed with intensities that are both weighted and filtered ("wtgs" in Table 4). A signal is apparent at the $\sim$8.15 day$^{-1}$ orbital period of X1323−619 (see Table 1) in panel (c) but is seen with an even higher amplitude in panel (e). No peak stands out at this frequency in either panel (b) or (d). The peaks at 1.0 and 2.0 day$^{-1}$ in panel (c) are artifacts of the window function that were not removed by the whitening procedure.

Figure 23. Results of a sensitivity test in which sine waves with peak-to-peak amplitude $2 \times 0.07$ counts s$^{-1}$ and each of a range of frequencies were superposed onto the 1.5–12 keV light curve of the source X1323−619 (see the text). The power in the frequency bin nearest the frequency of the sine wave is shown normalized by a local average power. The colors and symbols show the powers obtained using different smoothing timescales (0.3 days, black filled circles; 0.9 days, green open triangles; 3.0 days, red stars; 10.0 days, deep blue filled squares; 30.0 days, black open circles; 100.0 days, cyan triangles; and 500.0 days, magenta stars).

A test was run to illustrate by example the sensitivity of the entire analysis procedure. For each of a set of logarithmically spaced frequencies that cover the full frequency range of our search, a sine wave was added (superposed) to the 1.5–12 keV light curve of X1323−619. The power in the frequency bin nearest the frequency of the sine wave is shown normalized by a local average power. The colors and symbols show the powers obtained using different smoothing timescales (0.3 days, black filled circles; 0.9 days, green open triangles; 3.0 days, red stars; 10.0 days, deep blue filled squares; 30.0 days, black open circles; 100.0 days, cyan triangles; and 500.0 days, magenta stars).
light curve of the source X1323–619, and the entire analysis was then performed on the modified light curve. To be precise, the sine wave was added after the times of each measurement were adjusted to the barycenter of the solar system, and before any other part of the analysis. The peak-to-peak amplitude of the sine wave was $2 \times 0.07$ counts s$^{-1}$ and the fractional frequency spacing was $\Delta f/f = 0.0123094$. For each frequency, the value of the power in the compressed and whitened power spectrum at the frequency closest to the frequency of the added sine wave was then obtained. These powers illustrate the “transmission” of the analysis as a function of frequency, even though the representation is imperfect, in part because the input sine wave amplitude is not too far above the noise level (on purpose so that the added sine waves do not affect the transmission). The analysis was done for each of the seven smoothing timescales 0.3 days, 0.9 days, 3.0 days, 10.0 days, 30.0 days, 100.0 days, and 500.0 days using the basic data weighting parameters and the Gaussian smoothing kernel.

The results are shown in Figure 23. The size of the frequency-to-frequency fluctuations in the plot is roughly consistent with what one would expect from the amplitude of the input sine waves relative to the noise. It is apparent that the sensitivity changes as a function of frequency. This may be understood by considering an equivalent analysis procedure, namely, the production of folded light curves where, for a fixed amount of data, more cycles are superposed for higher frequency signals and the more the averaging reduces the noise. In a folding analysis, the sensitivity to a given power should vary inversely with the size of the frequency--spacing was $0.3$ counts s$^{-1}$.

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