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DETECTION OF COHERENT 7.6 Hz OSCILLATIONS DURING A BURST FROM AQUILA X-1

R. J. SCHOELKOPF
Department of Physics, California Institute of Technology, Pasadena, CA 91125

AND

R. L. KELLEY
Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center, Code 666, Greenbelt, MD 20771
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ABSTRACT

We report the results of timing and spectral analysis of the X-ray source Aql X-1 (X1908+005) using data obtained with the *Einstein* SSS and MPC instruments. A classic type I burst was observed from Aql X-1 in both detectors, and a coherent modulation with a period of 131.66 ± 0.02 ms (7.6 Hz) and a pulsed fraction of 10% was detected in the SSS data (0.64–4.5 keV) during the period of enhanced emission. The signal has a random occurrence probability of less than 5×10^{-5}. The sensitivity of the MPC for high-resolution timing during the burst is greatly reduced because of the low-duty cycle (<10%) during the burst, and the modulation is not detected. There is no evidence for a loss of coherence during the ~80 s when it is observable, giving $f/\Delta f > 600$. The 2 σ upper limit on the rate of change of the pulse period is 5×10^{-5} s/s^{-1}. We argue that an asymmetrical burst occurring on a neutron star rotating at 7.6 Hz offers a plausible explanation for the oscillation.

Subject headings: stars: individual (Aql X-1) — stars: pulsation — X-rays: binaries — X-ray: bursts

1. INTRODUCTION

Among the many type I X-ray bursts that have been observed, evidence for periodic emission during bursts has been reported in only a few cases. The first result was reported by Mason et al. (1980) who found 27.5 ms (36.4 Hz) oscillations during an optical burst from X1254−690. The first evidence of X-ray oscillations during a burst was given by Sadeh et al. (1982). They reported 12.2 ms (82 Hz) oscillations in a burst from X1728−337 using the A-1 experiment aboard *HEAO 1*. This burst also shown to be erratic on a time scale of tens of milliseconds by Hoffman et al. (1979) using data from the A1 and A2 instruments on *HEAO 1*. The "rapid burster" (X1730−333) was found by Tawara et al. (1982) to exhibit 0.5 oscillations during two out of 63 type II bursts observed with the *Hakucho* satellite. They measured a 1% difference in period between the bursts separated by 31 hr and therefore ruled out rotation of the neutron star as a source of the oscillations. It is highly likely that these oscillations are related to the complex quasi-period oscillation (QPO) phenomena that are observed in the "rapid burster" (Stella et al. 1988). Recently, Murakami et al. (1987) have reported a 0.65 s oscillation in the burst flux from X1608−522 using data from the *Hakucho* satellite. A detailed analysis of the data from X1608−522 indicates that the burst envelope may be oscillating while radiating at the Eddington luminosity.

We have analyzed a type I burst from the X-ray burster Aql X-1 (X1908+005; Koyama et al. 1981) detected with the *Einstein* SSS that shows strong evidence for a 131 ms (7.6 Hz) oscillation that persists during the ~1 minute burst. The emission is very coherent ($f/\Delta f > 600$) and has a semi-amplitude that is ~10% of the total X-ray flux. Among the several physical mechanisms that might give rise to modulated burst flux, emission from a region that covers a fraction of the surface of a rotating neutron star appears to be the most plausible.

2. OBSERVATIONS AND ANALYSIS

Observations of Aql X-1 were carried out with the *Einstein Observatory* in April of 1979. The SSS was in the focal plane of observations of Aql X-1 on 1979 April 6, 7, and 10 resulting in ~17,000 s of net exposure. Two X-ray bursts were detected with the MPC and the second of these was captured simultaneously with the SSS. This burst took place at 16:54:20 UT on April 7. The MPC data from both bursts and the persistent X-ray emission have been analyzed in detail by Czerny, Czerny, & Grindlay (1987). They found that both of the bursts showed softening after the peak that is characteristic of type I X-ray bursts (see Lewin & Joss 1983, and references therein), but there was substantial emission after the main part of the burst, particularly in the case of the first burst. They were able to fit cooling blackbody spectra to the burst data, but obtained unacceptable fits near the burst peaks, probably due to large changes in temperature on a time scale less than 2.5 s. They also found that the emitting area was changing with time and interpreted this as a change in the fraction of the neutron star that is emitting at the derived blackbody temperature.

We have analyzed the SSS data from the second of the two bursts simultaneously with the MPC data. In Figure 1 we show the SSS counts in the 0.6–4.5 keV range (in 200 ms bins) versus time for this event. The combined SSS/MPC spectrum of the persistent emission, over the energy range 0.6–20.0 keV, is well fitted by optically thin thermal bremsstrahlung with a temperature of 4.7 keV and hydrogen column density $N_{\rm H} \sim 5.0 \times 10^{21}$ cm^{-2}. The persistent emission has an unabsorbed energy flux of 7.3×10^{-9} ergs s^{-1} cm^{-2} in the 0.6–20 keV energy band.

For the burst spectrum, Czerny, Czerny, & Grindlay (1987) were unable to obtain acceptable fits to a blackbody spectrum near the burst peak. This is probably due in part to rapid changes in temperature, but the actual spectrum may be more

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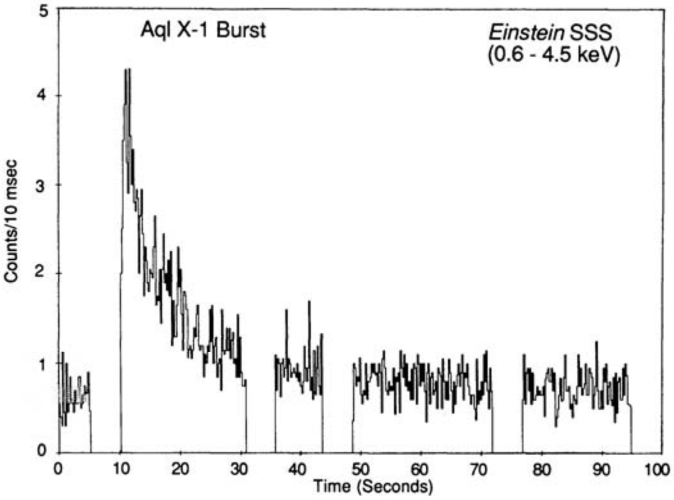

FIG. 1.—*Einstein* SSS light curve of the type I burst from Aql X-1 (X1908+005) on 1979 April 7. The counting rate is in units of counts per 10 ms in the 0.6–4.5 keV energy range. Time is in seconds relative to 16:54:10 UT.

complicated due to scattering in the photosphere or if there is reprocessing in the accretion disk. We have fitted a blackbody plus a thermal bremsstrahlung spectrum to the SSS data alone, with the thermal bremsstrahlung parameters held fixed at the preburst values. A very good fit was obtained with a blackbody temperature of 1.26 keV near the peak of the burst. This value, however, is inconsistent with the MPC data alone (which gives a peak temperature of ~ 2.5 keV despite the poor fit; see Czerny, Czerny, & Grindlay 1987), and indicates that more than a single blackbody component is present. For the purposes of a flux determination, the fit to the SSS spectrum is sufficient and gives a value of 1.1×10^{-8} ergs s^{-1} cm^{-2} in the 0.6–4.5 keV band. The MPC data yield 6.7×10^{-8} ergs s^{-1} cm^{-2} for the range 1.2–20 keV. These are unabsorbed total fluxes that include the contribution from the persistent emission during the burst.

For this series of observations the total counting rates from the SSS detector are available (without any spectral information but with negligible deadtime per readout) in 10 ms bins. The SSS detector has been described by Joyce et al. (1978), and the MPC has been described by Gaillardetz et al. (1978) and Grindlay et al. (1980). The high-speed MPC data from the Time Interval Processor (TIP) are available as photon arrival times with microsecond resolution, but due to dead-time effects, the statistical quality of the TIP data is much lower than that of the SSS data in the present case. This is discussed further below.

For the SSS data, we analyzed segments of data using the standard Fast Fourier Transform (FFT) routine. Figure 2 shows three power spectra computed from the SSS data, each of 80 s duration (8192 points) from immediately before, during, and after the burst. The data show strong evidence for a coherent modulation at 7.6 Hz which is present *only* during the burst. The power shows up only in one frequency bin, from which we infer a coherence limited by the length of the data set. This gives $f/\Delta f > 600$, where Δf is the FWHM of the spectral feature. The second largest peak in the power spectrum, although not independently significant, occurs precisely at 22.8 Hz, or 3 times the fundamental frequency, and represents additional power in the modulation due to a nonsinusoidal pulse shape. The power spectrum (when examined in log-log coordinates) is flat above ~ 3 Hz, and is consistent with purely Poissonian noise (except for the single bins at 7.6 Hz and 22.8 Hz). The power spectrum of the data window function has no features at or near these frequencies. The 7.6 Hz feature is a factor of 15.8 above the mean power and has a chance occurrence probability of 5.6×10^{-4} in 4096 independent frequency bins (equivalent to $\sim 3.5\,\sigma$).

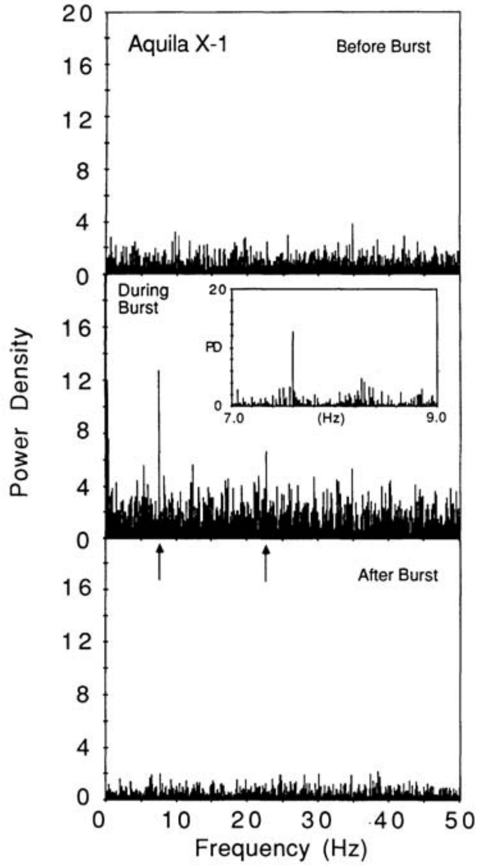

FIG. 2.—Power spectra formed from equal intervals (80 s each) of SSS data near the burst. The power is normalized such that the mean power density of a steady source is equal to the variance due to photon counting statistics. The strong modulation at 7.6 Hz and the second harmonic at 22.8 Hz (3×7.6 Hz) are indicated by the arrows and are present only during the burst. The excess power at very low frequencies during the burst is due to the (roughly) exponential burst itself. The mean power density above 3 Hz is ~ 0.8, so the 7.6 Hz feature is more than 15 times higher than the mean power density.

To include the effect of the harmonics, in particular the second harmonic (i.e., $3\omega t$), which has an amplitude of 7.6 times the mean power density, we computed the probability of obtaining the largest power observed over a range of frequency bins at each of the five possible harmonics up to the Nyquist frequency. These probabilities were then multiplied to obtain the total chance occurrence probability of detecting the power obtained at the fundamental frequency and each of the harmonics in 4096 independent frequency bins. The result is 5.4×10^{-5} and is equivalent to a $\sim 4.1\,\sigma$ detection.

To study the periodicity further, we divided the burst interval into two segments, each lasting 25 s. Figure 3 shows periodograms that were formed by folding each of the segments with respect to a range of trial periods and then computing chi-squared for a constant source intensity. The modulation period

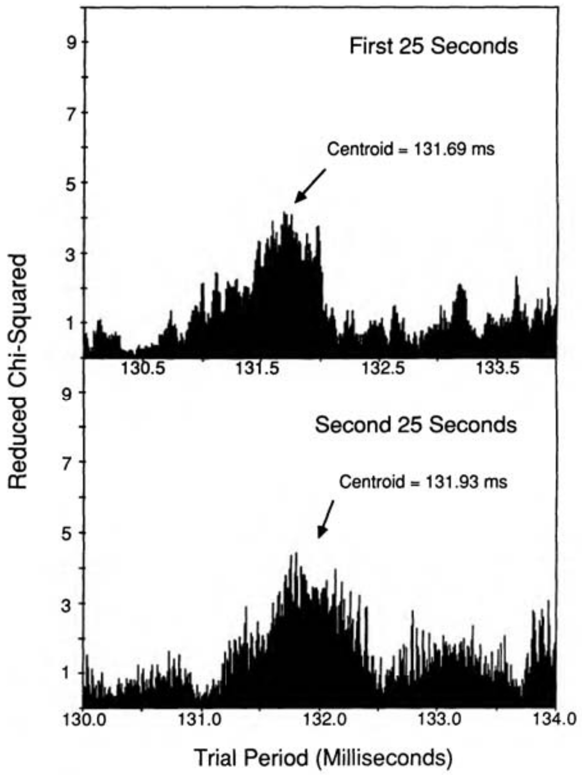

FIG. 3.—Periodograms of two subsets of the SSS data, each 25 s long. The 7.6 Hz oscillation is detectable in each segment of data. Periods in this range have been oversampled by a factor of ~10, so that not all bins are statistically independent. The formal difference in periods corresponds to a $\dot{P}$ of $+1 \times 10^{-5}$ s s^{-1}; the 2 σ upper limit on the pulse period derivative is 5×10^{-5} s s^{-1}.

for each segment was obtained from the centroid and the uncertainties were derived using the chi-squared distribution for 68% confidence. No significant change in period was found: the 2 σ upper limit on $\dot{P}$ is 5×10^{-5} s s^{-1}.

For a more precise determination of the period, the two segments were again folded modulo a trail period and a sine wave was fitted to each of the segments. The period was then adjusted to give no phase shift between the two segments. Since the period is not changing on a time scale measurable from the data, this gives the best estimate of the pulse period. This procedure gives a period of 131.66 ± 0.02 ms and a semi-amplitude for each of the segments of 10% and 9% of the total X-ray flux, respectively. The folded light curve for the best-fit period is shown in Figure 4.

We have also examined the high time resolution (TIP) data from the *Einstein* MPC detector that were obtained simultaneously during the burst. Photon arrival times (to the nearest microsecond) were stored in a buffer which recorded up to 512 events and was normally read out every 2.56 s. As a result, numerous large gaps occur for observations of bright sources. For the segment of data including the burst, the TIP data has ~6% coverage. The FFT of the burst data from the MPC/TIP has no significant features near 7.6 Hz.

In order to determine whether the lack of a detection in the MPC is consistent with the 10% modulation observed with the SSS, we performed a numerical simulation. First, we constructed a simulated light curve based on the parameters

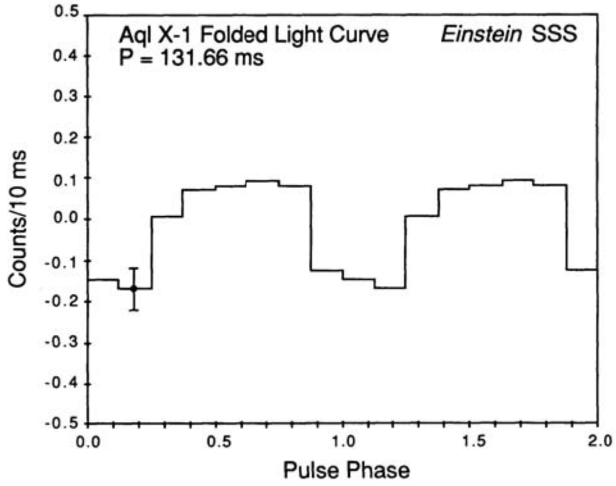

FIG. 4.—Folded light curve of 50 s of SSS data during the burst for a period for 131.66 ms. The semi-amplitude of the modulation is ~10% of the total X-ray flux.

derived from the analysis of the SSS data. We superposed an exponential burst on a persistent flux component, and introduced a modulation with a 131 ms period which represented a constant fraction of the additional emission during the burst. We then introduced gaps in the simulated data that coincide exactly with the actual gap structure of the MPC data, and Fourier analyzed the resultant simulated data set. There was no detection of the modulation at the 10% pulsed fraction indicated by the SSS data and the power spectrum of the simulation was entirely consistent with the power spectrum of the actual data (i.e., the effects of the gaps were correctly reproduced). By arbitarily increasing the pulsed fraction of the simulated data, we obtain an upper limit on the pulsed fraction for detection in the MPC energy band (1.3–20 keV) of 45%. At this level, the 7.6 Hz feature would become significant at the 99% confidence level in the power spectrum of the simulated data. Multiple sidelobes are also present, verifying that the sensitivity of the MPC to this modulation has been significantly decreased by the spreading of power due to the window function.

By Fourier analyzing ~1300 s (one transform of 2^{17} points) of the SSS data which do not include the burst, we derive an upper limit of ~2% on the pulsed fraction of the persistent emission in the frequency range 0.01 − 50 Hz. The periodic behavior is therefore seen to be strongly correlated with the burst activity and does not become detected merely due to the increase in total source flux.

3. DISCUSSION

Several models have been proposed for producing coherent modulations in X-ray bursters with periods in the 10–100 ms range (Livio & Bath 1982). These include mechanisms for revealing the underlying spin of the neutron star, nonradial oscillations of the neutron star envelope, oscillations of the photosphere under radiation pressure from the source while radiating at the Eddington limit, orbiting material which periodically obscures the central X-ray source, and oscillations in the accretion disk surrounding the neutron star. Any such model for Aql X-1 must be able to account for oscillations which occur only during the burst, and for the observed coherence ($f/\Delta f > 600$).

Although there have been no direct observations of neutron star spin rates in low-mass X-ray binaries (Cominsky et al. 1980; Leahy et al. 1983; Mereghetti & Grindlay 1987), it has been pointed out that since these systems are highly evolved, one may expect the neutron stars to have been spun up to high rotation rates (i.e., $P < 100$ ms) due to accretion torques (van den Heuvel 1988, and references therein).

The high coherence of the oscillations immediately suggests that rotation of the neutron star is involved. If it were possible to produce a weak asymmetry in the temperature over the neutron star surface during a burst, oscillations in the burst flux could be produced by viewing a finite region of higher temperature as the neutron star rotates. In the present case, a difference of $\sim 2\%$ in the temperature over a large fraction of the neutron star surface would be sufficient to account for the emission. In fact, Czerny, Czerny, & Grindlay (1987) have found that the emission from the burst occurred over an area that is less than the full area of the neutron star by fitting a cooling blackbody as a function of time and deriving the temperature and the emitting area (assuming a constant radius).

Balucinska & Czerny (1985) have also found evidence for nonspherically symmetric emission in X-ray bursts from X1837+049 (Ser X-1). They found that in nearly all cases studied, only about half of the total surface area is involved during a burst, assuming that the color and effective temperatures are the same, and that the X-ray emission is not substantially beamed. Thus, due to the likely nonuniformities in the X-ray emission during a burst, and the expected high rotation frequencies of neutron stars, this mechanism offers the simplest explanation for the 7.6 Hz oscillations in Aql X-1. An observable consequence of this model is that there should be changes in the pulse shape with time, especially during the burst rise. We note that this model cannot explain the large period derivatives (10^{-5}–10^{-6} s s^{-1}) reported for 4U1907+09 by Sadeh & Livio (1982); if the neutron star changes its period at this rate it requires changes in rotational energy at a level of greater than $\sim 10^{43}$ ergs s^{-1}.

Fryxell & Woosley (1982) have show that it may take as long as ~ 8 s for a deflagration wave to propagate around a neutron star, so that oscillations in the burst flux may be expected minimally during the burst rise. The required anisotropy of the X-ray emission may be maintained by a magnetic field of intermediate strength (e.g., $< 10^{11}$ G), or if the nuclear burning does not fully envelop the entire surface due to large variations in the mass distribution prior to the burst (e.g., due to disk accretion and/or the effects of rotation).

Note that in the context of the accretion spin-up scenario for the formation of rapidly spinning neutron stars from low-mass X-ray binaries, the relatively low spin rate (7.6 Hz) may not be unexpected due to the transient nature of Aql X-1 (Priedhorsky & Terrell 1984, and references therein), although this may require that the source be in a state of low-mass transfer for periods of time longer than currently observed.

The periods for nonradial oscillations of a neutron star envelope have been calculated (McDermott & Taam 1987, and references therein), and only the so-called "g-mode" oscillations are expected to have periods greater than ~ 1 μs. McDermott and Taam point out the possibility that these modes might be excited by a thermonuclear flash or sudden accretion event; in fact, the energy required for exciting these modes to large amplitudes is only $\sim 10^{-4}$ of the energy released in a typical X-ray burst. However, they also predict that the g-mode oscillations should be heavily damped, perhaps persisting only for 10–100 cycles, and should increase in period at a rate of $\sim 10^3$ s s^{-1}. This prediction is in contradiction with the observed persistence of the oscillations. The periods are also predicted to scale with the spherical harmonic index, l, of the oscillations as $[l(l+1)]^{-1/2}$, which would place several different-order modes in the period ranges searched. Unless there is a mechanism for preferentially exciting only one mode, we expect the source to simultaneously display some of these other harmonics. There is no suggestion in the observations for oscillations at the predicted periods.

Periodicities could also be caused by obscuring material which is orbiting the neutron star. The radius of a Keplerian orbit with a frequency of ~ 7.6 Hz around a 1.4 $M_{\odot}$ neutron star is ~ 400 km. To cause a modulation with the observed narrowness in frequency, the spread in radial extent would have to be correspondingly narrow, i.e., $\sim 0.1\%$ of the radius of rotation. If we associate this radius with that of a magnetosphere, we infer a surface magnetic field of $\sim 2 \times 10^{10}$ G for a luminosity from the persistent emission of $\sim 3.5 \times 10^{36}$ ergs s^{-1} $\times$ $(D/2\ \mathrm{kpc})^2$ (Thorstensen, Charles, & Boyer 1978). The modulation might therefore be caused by clumping of material orbiting at the edge of the magnetosphere. However, the observed persistence of the oscillations requires the clumps to be highly stable over many orbits. In addition, the clumps must somehow be created by the burst itself, since the oscillation is not present in the nonburst emission. A model which involves gating of mass transfer by an interaction of the magnetosphere and the accretion disk has been proposed to explain the phenomenon of QPOs (van der Klis 1989, and references therein). The behavior we observe, however, is essentially different from the QPOs, which have effective coherences, $f/\Delta f$, of < 10. Livio & Bath (1982) point out that disk oscillations could produce periods in the range observed but argue that these are unlikely to explain the observations. These models are also likely to produce low-coherence signals.

Murakami et al. (1987) have observed somewhat slower oscillations (0.6 s) during the decay of an X-ray burst from X1608−522. Their observations show strong evidence for radial oscillations of the emitting region, and they argue that, on the basis of energetic considerations, the photosphere around the neutron star may be unstable during the contracting phase (also see Shibazaki & Ebisuzaki 1989). We are unable to distinguish whether this behavior could also be occurring in Aql X-1. However, it is unclear whether such a model could account for the other occurrences of rapid, higher coherence oscillations during bursts.

At present, non spherically symmetric bursts on a rotating neutron star provide a natural explanation for the observed coherent 7.6 Hz oscillations. A temperature amplitude of $\sim 2\%$ over a large fraction of the surface of the neutron star (actually the X-ray–emitting photosphere) during the burst is all that is required to produce the observed modulation, and in fact analysis of the burst spectrum suggests that this in indeed the case. The likelihood that type I bursts do not occur simulataneously over the surface due to finite propagation times, the effects of disk accretion, rapid rotation, and perhaps a weak magnetic field, means that variability and perhaps even oscillations, in the X-ray flux from type I bursts may be common but will require instruments with sufficiently high collecting areas over large bandwidths and high time resolution. Low-mass X-ray binaries have been proposed as intermediaries in some evolutionary scenarios for the production of binary and millisecond pulsars. Oscillations during X-ray bursts may thus provide a new probe into the spin rates of neutron stars during the low mass X-ray binary phase of such systems. Clearly, observations of larger numbers of bursts are necessary (e.g., with archival *EXOSAT* data, *Ginga*, and XTE) to permit an understanding of this potentially important phenomenon.

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