FAST OSCILLATIONS IN VARIABLE X-RAY SOURCES AND X-RAY BURSTERS

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ABSTRACT. The properties of coherent oscillations with periods of tens of milliseconds that have been observed in seven variable X-ray sources and bursters are reviewed. Theoretical models for the generation of the oscillations are discussed. Difficulties with a magnetic rotator model are indicated. It is suggested that at least in several cases, g-mode oscillations of the neutron star provide a satisfactory explanation of the observations.

1. OBSERVATIONS

Recent observations have revealed the presence of periodicities of the order of tens to hundreds of milliseconds in several X-ray sources that are either variables or that have been identified as burst sources. Table I summarizes some of the properties of these sources.

Theoretical models for the observed periodicities are discussed in section 2 and a comparison of these models is carried out in section 3. A comparison of the properties of the oscillations with the coherent oscillations of dwarf novae is conducted in section 4.

2. THEORETICAL MODELS

We will now attempt to study possible models for the generation of the observed periodicities, following the work of Livio and Bath (1982, see also Livio, 1982).

Three major classes of models will be discussed;

a) Neutron star magnetic rotator model.
b) Luminous blobs in the accretion disk.
c) Neutron star oscillations

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TABLE I

Observed Coherent Oscillations

Source	Type	Period (ms)	$\dot{P}$	Duration of Pulsations	Pulsed Fraction	Ref.
MXB 1728-34	X-ray Burster	12.25	-10^{-6}	~40 sec	3%	1
4U1907+09	Variable X-ray source, binary	15.2	$+10^{-5}$	~10 sec (several times)	12%	2
A0538-66	Recurrent X-ray transient, binary	69.2	$+5\times10^{-10}$	~3900 sec	26%	3,4
4U1254-69	Optical burst observed	27.47	No data	~40 sec	5%	5
2103+09	No known source. Increase in X-ray intensity.	67.55	Not observed	~5000 sec	1.5%	6
2100-79	Coincides with weak HEAO source	15.85 (evidence)	$\lesssim 10^{-16}$	Observed for 8 days	~70%	7
MXB1730-335	Rapid burster	503,508	No data	~240 sec	No data	8

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2.1 Magnetic Rotator

Rotation is probably the easiest way to obtain a singly periodic signal. The possibility that the periodicities are generated by a rotating magnetic neutron star should, therefore, be investigated. Three points that have to be discussed in the context of such a model are: (i) The generation of a modulated signal, (ii) Period changes, (iii) The duration of the periodicities.

2.1.1. Modulation of signal. Magnetic fields are believed to be the agent via which the accreted matter is funnelled onto a small cap on the neutron star's surface, thus generating a "spot" which in turn, as the neutron star rotates, produces the modulated emission. The area of the caps decreases with increasing magnetic field strength.

This same magnetic field, however, can enforce plasma corotation up to the Alfven radius and thus may inhibit accretion altogether, if the Alfven radius is larger than the corotation radius, because of the matter's inability to overcome the centrifugal barrier.

In order to illustrate the competition between these two conflicting effects we shall use for the area of the magnetic caps the expression obtained by Arons and Lea (1980), although their formula is really inapplicable in the case of fast rotators of the type we are discussing. Assuming typical values for the X-ray luminosity-L_X, temperature-T_X and for the neutron star radius R_X and taking a representative period of P=0.02 sec, the two requirements that: (a) the caps do not cover the whole neutron star surface and (b) the Alfven radius is smaller than the corotation radius, lead to:

$A_{mag.caps} \lesssim A_{n.s.}$	$R_{Alf.} \lesssim R_{cor.}$
$L_x \sim 10^{37}$ ergs s^{-1}	$L_x \sim 10^{37}$ ergs s^{-1}
$T_x \sim 7$ keV	$R_x \sim 10^6$ cm
$R_x \sim 10^6$ cm	$P \sim 0.02$ sec
$\mu_{30}^{1.652}+0.34\ \mu_{30}^{2.566} \gtrsim 0.1$	$R_A \sim 3\mathrm{x}10^8 \mu_{30}^{4/7} L_{x37}^{-2/7} R_{x6}^{-2/7} M_{x\odot}^{1/7}$ cm
	$R_C \sim 1.1\mathrm{x}10^7 M_{x\odot}^{1/3} P_{0.02}^{3/3}$ cm
	$R_A \lesssim R_C$
$\mu_{30} \gtrsim 0.25$	$\mu_{30} \lesssim 0.003$

Clearly the two requirements are inconsistent. This is probably not an insurmountable difficulty because of the inapplicability of the formula used for the cap area. In this respect it is enough to note that simple, kinematical estimates give much smaller values (e.g. Davidson and Ostriker 1973) for the same parameters

$$\frac{A_{mag.caps}}{A_{n.s.}} \sim 8\mathrm{x}10^{-4}\ \mu_{30}^{-0.57} \qquad (1)$$

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2.1.2. Funnelling and bursts. A second problem that may be associated with strong funnelling relates to the possible inhibition of X-ray bursts. On one hand, as a result of strong funnelling onto a small fraction of the neutron star surface area, the effective accretion rate is increased to

$$\dot{M}_{EFF} \sim 7.5\times10^{18} L_{x37} R_{x6} M_{x\odot}^{-1} \left(\frac{A_{n.s.}/A_{mag\ caps}}{10}\right) g\ s^{-1} \tag{2}$$

On the other hand, an increase in the accretion rate results in strong compressional heating, relatively early helium ignition and therefore, weak electron degeneracy. Consequently, as it has been found in the detailed study of Ayasli and Joss (1982), the thermonuclear flashes are essentially suppressed at accretion rates above $3\times10^{18} g\ s^{-1}$ thus, leading to a non bursting situation. Now, among the sources in which the periodicities have been detected, at least two, MXB 1728-34 and MXB 1730-335 and possibly three (an optical burst has been observed from 4U1254-69) are bursters. The magnetic rotator scenario may have, therefore, additional difficulties in this respect.

2.1.3. Changes in period. When a rotator model is considered an important point that has to be addressed is that of the observed period changes. At least three different mechanisms can be invoked to produce changes in the period: (i) A changing Doppler shift due to orbital motion. In this case the rate of change in the period is given by

$$\dot{P} \sim 9\times10^{-8} \left(\frac{d}{10^{11} cm}\right)^{-2} P_{0.02} \left(\frac{M_{tot}}{10\ M_{\odot}}\right) \tag{3}$$

where d is the binary separation and M_{tot} is the total mass of the system. Expression (3) gives very good agreement with the observations of A0538-66 (Skinner et al. 1982b, Charles et al. 1982), however, it definitely cannot explain the $\dot{P}$'s of 4U1907+09 (which is known to have an orbital period of 8.38 days, Marshall and Ricketts 1980) and of MXB 1728-34. (ii) Braking by magnetorotational radiation in the initial spin-down phase. In this case the $\dot{P}$ is given by (e.g. Lipunov 1982, Illarionov and Sunyaev 1975).

$$\dot{P} \sim 5\times10^{-14} P_{0.02}^{-1} \mu_{30}^{2} I_{45}^{-1} \tag{4}$$

where I_{45} is the moment of inertia (in units of $10^{45} g\ cm^2$), so that besides being too low for at least two of the observed $\dot{P}$'s, it clearly cannot account for the spin-up observed in MXB 1728-34. (iii) Spin-up in an accreting X-ray pulsar. The maximal spin-up rate, for a neutron star accreting from a disk is given by (Ghosh and Lamb 1979)

$$-\dot{P} \sim 6.3\times10^{-16} \mu_{30}^{2/7} \alpha(\omega_s) R_{x6}^{6/7} M_{x\odot}^{-3/7} I_{45}^{-1} P_{0.02}^{2} L_{x37}^{6/7} \tag{5}$$

where

$$\omega_s \sim 67.5 \mu_{30}^{6/7} R_{x6}^{-3/7} M_{x\odot}^{-2/7} P_{0.02}^{-1} L_{x37}^{-3/7} \tag{6}$$

and the function $\alpha(\omega_s)$ was computed by Ghosh and Lamb (1979). This spin-up rate cannot, again, explain some of the observed $\dot{P}$'s. Furthermore, it does, in fact, apply only to slow rotators. For the fast rotators discussed here, the near cancellation of magnetic and material stresses will, in fact, result in much lower rates.

Finally, we would like to point out that even from energy considerations alone, the difficulty associated with period changes can be illustrated by noting that

$$\dot{P} \sim 2\times10^{-13} \left(\frac{\dot{E}}{10^{39}\,\mathrm{ergs\ s^{-1}}}\right) I_{45}^{-1} P_{0.02}^{3} \tag{7}$$

and recalling that the energy involved in X-ray bursts is of the order of 10^{39} ergs, making high $\dot{P}$'s very difficult to explain.

2.1.4. Duration of periodicities. In any magnetic rotator scenario it is expected that the flux will be pulsed at all times, including at quiescence (if bursters are involved). Difficulties in the detectability of the periodic signal may weaken the last statement to the requirement that the periodicities should be detectable in all bursts and increased luminosity states. This requirement is essentially model independent, as far as details of the rotator are concerned. The observational situation for some of the sources is summarized in Table II. It clearly demonstrates that severe difficulties are posed to the magnetic rotator model (for these sources).

All the problems associated with rotation that have been discussed motivate the search for other models for the origin of the oscillations. We will discuss here two additional possible scenarios.

2.2. Luminous Blobs in Disks

The Keplerian motion of hot, luminous blobs in the accretion disk has been originally suggested by Bath (1973) as the source of the coherent oscillations observed in dwarf novae. It is possible therefore, in principle, that similar blobs orbiting the neutron star produce the periodicities under discussion. The Keplerian period of such a blob is given by

$$P_{Kep} \sim 17\, M_{x\odot}^{-1/2} \left(\frac{R_{orb}}{10^{7}\,\mathrm{cm}}\right)^{3/2} \mathrm{ms} \tag{8}$$

where R_{orb} is the orbital radius of the blob. Since the transition between the gas pressure dominated and radiation pressure dominated regions in standard steady disk models occurs at (Novikov and Thorne 1973)

$$R_{mid\text{-}in} \sim 1.2\times10^{7}\, \alpha^{2/21} M_{x\odot}^{1/3} \dot{M}_{17}^{16/21} \mathrm{cm} \tag{9}$$

where α is the usual viscosity parameter (Shakura and Sunyaev 1973), Keplerian periods in the middle or inner parts of the disk agree well

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TABLE II

Observational situation concerning the duration of periodicities

Source	Observations
MXB 1728-34	1) No 12 ms period in DC flux 2) Periodicity observed only in one out of four bursts. 3) Most of the periodic signal coincides with bursts.
A0538-66	Pulsations detected at 40 MPC counts/sec, not detected at 10 counts/sec (although should have been detected at the same pulsed fraction).
4U1907+09	Periodicity observed only in 3 (possibly 4) out of 20 passes. In two of them the source was in a high state.
4U1254-69	No periodic modulation was found in entire data set. The period was found in data only from the immediate vicinity of the burst.
MXB 1730-335	1) Oscillations discovered only in two trapezoidal bursts. 2) Do not appear as due to neutron star rotation.

with the observed ones.

In view of the apparent phase stability of the oscillations (in several cases), however, the lifetime of such blobs against smearing by differential rotation should be considered. This lifetime is roughly given by (Bath, Evans and Papaloizou 1974)

$$\tau \lesssim \frac{2}{3}\frac{PR_{orb}}{D} \tag{10}$$

where D is the radial dimension of the blob. If we assume that

$$D \sim h(R_{orb}) \tag{11}$$

where h is the local disk thickness, we obtain for steady disk models a lifetime of

$$\tau \sim \begin{cases} 1.1\ \alpha^{1/10} P_{0.02}^{29/30} M_{x\odot}^{1/3} \dot{M}_{17}^{-1/5}\ \text{sec} & \text{in middle region} \\ 1.5\ P_{0.02}^{5/3} M_{x\odot}^{1/3} \dot{M}_{17}\ \text{sec} & \text{in inner region} \end{cases} \tag{12}$$

which seems too short to account for the observed duration of the periodicities, even when considering the uncertainties involved in (12).

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2.3 Non Radial Oscillations of Neutron Star

The properties of several non radial modes of neutron stars are summarized in Table III (see Van Horn 1980). The shortness of the periods and the fact that gravitational radiation causes the damping of p-modes (for $\ell \gtrsim 2$) on an extremely short timescale $\tau_{Grav.} \lesssim 2$ sec, probably excludes them as a possible origin of the oscillations.

TABLE III

Properties of neutron star oscillation modes (low order)

	p-modes	g-modes	r-modes	Torsional Modes
Period	0.1 - 1 ms	10 - 1000 ms	P_{rot}	~20 ms
Damping	τ_{Grav}	τ_{Therm}	τ_{Rot}	τ_{Crust}
Excitation	Thermonuclear events	Thermonuclear events	Thermonuclear events	Thermonuclear events
	Mass transfer events	Mass transfer events	Mass transfer events	Mass transfer events
		Shear	Shear	Shear

We will now examine more closely the properties of g-mode oscillations. Analytic estimates of the periods give (Van Horn 1980, Livio and Bath 1982)

$$P_g \sim \frac{49}{[\ell(\ell+1)]^{1/2}} R_{x6} \, \Pi_{22}^{-1/2} \, \rho_6^{1/2} \quad \text{ms} \tag{13}$$

where Π_{22} is the pressure in units of 10^{22} dynes cm^{-2} and ρ_6 is the density in units of 10^6 g/cc.

Numerical calculations (Van Horn et al. 1982) using neutron star models give for g_1-g_3 periods of $P_g \sim 66$-81 ms for a neutron star mass of 1.326 $M_\odot$ and $P_g \sim 371$-692 ms for a mass of 0.503 $M_\odot$ (which may however be too small to be formed in a collapse followed by a supernova explosion).

An additional feature that was demonstrated by the numerical calculations was the confinement of the oscillations to the outermost layers of the neutron star. This fact may have two important consequences: (i) It makes the excitation of the modes by surface phenomena (such as thermonuclear or accretion events) easier and (ii) It may explain the observed changes in the period.

With respect to the first point here, we note that Van Horn et al. (1982) have concluded that the energy released in bursts is sufficient to excite the low order g-modes. Furthermore, the simulation of an accretion event by Starrfield et al. (1982) has resulted in a "ringing" of the neutron star's envelope with a period of ~200 ms. As for the second point (period changes), this represents a change in the structure of the region of mode concentration. If, based on the observed time-scale for changes in several sources, one demands $\tau_{Therm} \sim 10$ sec, then, one obtains for the mass involved in the changes

$$\Delta M \sim 10^{21}\ L_{x37}\tau_{10}\Pi_{22}^{-1}\rho_6 \quad g \tag{14}$$

which is a typical mass accreted prior to the burst (Ayasli and Joss 1982).

We thus conclude that g-modes have most of the observed properties for several sources. An important observational test of the g-mode hypothesis will be to determine whether several periods are ever excited simultaneously. So far, only the strongest signal in the power spectra has been studied, in most of the observations.

3. AGREEMENT OF THEORETICAL MODELS WITH OBSERVATIONS

In Tables IVa and IVb we have attempted to summarize some of the difficulties and agreements met by what we feel are the representatives of two major classes of models, with observations. With a total number of 7 sources so far, in which periodicities have been detected, an over division into subgroups does not seem wise, however, there does seem to emerge a suggestive distinction between two subclasses of objects. One contains the sources with short lived lower Q oscillations, for which the g-mode hypothesis seems to fit the observations better than rotation (Table IVa). Rotation seems to work quite well for the second group (Table IVb). One source, A0538-66, could perhaps be classified in both groups (the fact that the oscillations were not observed at turn-on are a strong point against rotation, which works very well otherwise). Clearly, many more observations will be required to decide among the various possible models.

It is very tempting to compare the observed periodicities in variable X-ray sources and bursters with the familiar coherent oscillations observed in cataclysmic variables. Such a comparison is presented in Table V.

TABLE IVa

Agreement of Theoretical Models with Observations

Source	Agreement and Difficulties with Rotation	Agreement with Difficulties with g-modes
MXB1728-34	Difficulties: 1) $\dot{P}$ too large 2) Duration of periodicities 3) Bursts not favoured by funnelling	Difficulties: 1) Only one period observed Agreement: 1) Excitation by bursts 2) $\dot{P}$ agrees with mass accreted between bursts
4U1907+09	Difficulties: 1) $\dot{P}$ too large 2) Duration of periodicities	Difficulties: 1) Only one period observed 2) Excitation not clear (once seen in low state) Agreement: 1) Excitation by accretion events?
MXB1730-335	Difficulties: 1) Period change 2) Duration of periodicities	Agreement: 1) Excitation by bursts
4U1254-69	Difficulties: 1) Duration of periodicities	Agreement: 1) Excitation by burst

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TABLE IVb

Agreement of Theoretical Models with Observations

Source	Agreement and difficulties with rotation	Agreement and difficulties with g-modes
A0538-66	Difficulties: 1) Not seen at turn on Agreement: 1) $\dot{P}$ agrees well with orbital Doppler shift 2) Duration quite long	Agreement: 1) Could be excited by accretion event.
2103+09	Agreement: 1) No observed $\dot{P}$ 2) Duration long	
2100-79	Agreement: 1) $\dot{P}$ very low 2) Duration long 3) Large pulsed fraction	

4. Comparison with "classical" cataclysmic variables

One cannot escape noticing a few quite striking similarities between the two types of oscillations. A question that therefore naturally arises (although caution is always advisable in making such analogies) is whether we are not observing the same phenomenon in the two classes of objects, the only difference being the nature of the compact object, a neutron star (in the "new" CV's) instead of a white dwarf (in the "classical" CV's).

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TABLE V

Comparison with "Classical" Cataclysmic Variables

	"Classical" CV's	"New" CV's
Periods	8-39 sec	12-508 ms
Lifetime/Period	$\sim 10^3$	$\sim 10^3 - 10^6$
P/P_{radial}	~10	~10
$P/P_{g\text{-}mode}$	~1	~1
$P/\dot{P}$	$10^5 - 10^7$ sec	$10^3 - 10^{14}$ sec
Relation to Activity	Seen only during outburst	In several sources seen at outburst or sudden increase of luminosity

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DISCUSSION FOLLOWING M. LIVIO'S TALK

ROBINSON: I don't think you should be particularly worried about there just being one oscillation there, what you really have is one detected oscillation and limits on the amplitudes of any other oscillations and my impression in looking at your power spectra is that those limits are very poor, you could easily have oscillations in there, with amplitudes up to 50% as large as the main one. In the case of the single white dwarfs in the field, that we know are pulsating, like ZZ Ceti stars, every one is multi-periodic, but many of them have power spectra that are dominated by just one oscillation, and if you would put a lot of noise on top of their light curves you would detect just that one oscillation. Then there is a question, why do you restrict yourself to g-modes? There are lots of different things.

LIVIO: I picked g-modes just to illustrate my point. In fact, the torsional modes may fit just as well. I also agree of course, with your former point, it strengthens the case for oscillations.

WARNER: I agree with Rob that perhaps the comparison with the isolated white dwarfs is better rather than the very impressive correlation that you have between the properties of the cataclysmic variables and your neutron stars. The interpretation of the oscillations in cataclysmics is certainly not agreed on and I doubt if very many people would say that they are g-mode oscillations. If you accept that the cataclysmics are more likely blobs in disks, can you make any comment on the possibility of that model applying to the neutron stars?

LIVIO: All that I can say is that like in cataclysmic variables, the periods are always longer than the Keplerian period right near the surface of the neutron star. There is a problem with the lifetime. The disks in cataclysmics are different than those around neutron stars in that the latter have also "middle" and "inner" zones in the standard disk models and this causes the short lifetimes. Another possibility is that this is not a blob, perhaps, but rather an oscillation mode of the disk, because there, always the periods are of the order of the Keplerian one. The problem is that very little is known about the excitation of those modes and their decay times.

CHANMUGAM: I just want to make a comment that while it is true that the periods of radial oscillations of neutron stars are much shorter than what you have here, you can have low mass neutron stars, say of mass 0.25 M_{o}, which have radial oscillation periods of the right order of magnitude. I don't know if such stars can be formed.

MAZEH: Do you expect such a high percentage of the modulation in the g-modes?

LIVIO: I don't know, it is not that high in all of them, there is one with 1.5% and one with 3%. For the two that have a very high pulsed fraction I have indicated that rotation probably works well.

LAMB: I have a couple of comments. One is that the group of objects that you have listed seems to be fairly heterogeneous and I am a little concerned about trying to find a common explanation for what may be a real menagerie of phenomena. There are possibilities that are not even explored here. For example, if you have accretion columns formed by magnetic flux tubes with plasma in them, the flux tubes can oscillate. There are also possible instabilities in the flow and so on.

LIVIO: I agree with you. I have tried to indicate the fact that different phenomena may be involved in my division of the objects into two classes and there may be more. It looks to me that the sources that are bursters or alike, look better with an oscillation explanation and the others look perhaps better with the rotation or something else. Regarding your second point, I have looked also into the type of shock-height oscillations in column accretion, which Steve Langer is going to talk about. It is not clear whether that phenomenon will work at all for neutron stars, where cyclotron cooling is important. The periods one obtains from their results, using, as an exercise, neutron star parameters, are a little bit shorter than the observed ones.

LAMB: I was really mentioning another possibility, that the plasma-filled flux tube could oscillate by itself.

BATH: I just want to point out that A0538-66 is an incredibly interesting object, in itself, it is a transient X-ray source with a strictly periodic outbursting behaviour. So one could program one's observations for the first time with transient sources.