Quasi-Periodic Oscillations

The Rapid Burster (MXB 1730-335)

Models vs. Observations - a Brief Review

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Abstract. The salient features of quasi-periodic oscillations (QPO) observed in type 2 bursts and in the persistent emission from the Rapid Burster are discussed. In addition, a brief review is given of the models that have recently been proposed to explain high-frequency QPO observed in several bright low-mass X-ray binaries. We do not yet know the mechanism(s) of the QPO, not even whether they are magnetospheric in origin. However, some of the proposed ideas could well be relevant to the various rather complex aspects of the QPO. It is likely that more than one mechanism is at work.

1. The Rapid Burster (MXB 1730-335)

1.1. Introduction

The Rapid Burster is a recurrent transient (probably a low mass X-ray binary, LMXB) located in a globular cluster. When the source is active, the accretion onto the neutron star can occur spasmodically resulting in type 2 bursts, or the accretion can be continuous, resulting in a persistent (though variable) X-ray flux. Type 2 bursts and persistent emission have been simultaneously observed. The type 2 bursts can last a few sec up to ~10 min. When they last longer than ~15 sec, in general, they have more or less "flat tops" (saturated flux) which can differ in their peak fluxes by factors up to 4. Therefore the saturated type 2 burst fluxes probably do not reflect an Eddington luminosity (except, perhaps for the highest bursts). For type 2 bursts, the waiting time to burst #n+1 is approximately linearly proportional to the integrated energy in burst #n; thus type 2 bursts behave like a relaxation oscillator. Type 1 bursts (presumably due to thermonuclear flashes on the surface of a neutron star) have also been observed from the Rapid Burster.

For references, see e.g., a review by Lewin and Joss 1983; Lewin et al. 1976; Lewin 1977; Ulmer et al. 1977; Hoffman, Marshall and Lewin 1978; White et al. 1978; Marshall et al. 1979; Van Paradijs, Cominsky and Lewin 1979; Basinska et al. 1980; Inoue et al. 1980; Tawara et al. 1982; Tanaka 1983; Pollard et al. 1983; Kunieda et al. 1984; Makino 1984; Lewin 1985; Tawara and De Yu Wang 1985; Lewin 1986.

The Rapid Burster is unique. There are other sources such as e.g., Cyg X-1, GX 301-2, (Hoffman, Marshall and Lewin 1978), and Cir X-1 (Tennant 1986) which show hiccups in their accretion, and, following Hoffman, Marshall and Lewin (1978), we call those type 2 bursts. However, none show the relaxation oscillator behavior as observed in the Rapid Burster. **The instability operating in the Rapid Burster is therefore probably different from those that produce type 2 bursts in other sources.**

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Many long type 2 bursts (with duration of a few times 10^2 sec) were detected by Tawara et al. (1982), using Hakucho. In 2 of 63 of these bursts, they discovered quasi-periodic oscillations (QPO) of ~2 Hz. The strength of the QPO (rms variation) was about 30%; in those bursts in which QPO were not observed, the upper limits were ~10%.

On August 28, 1985, EXOSAT observations were scheduled of 4U/MXB 1728-34 within ~0.5° of the Rapid Burster. Since the Rapid Burster was burst-active, the observations of 1728-34 were terminated, and the viewing direction of EXOSAT was changed for maximum possible exposure of the Rapid Burster, with 1728-34 just outside the field of view. Persistent emission and very long type 2 bursts (~3-12 min) were observed (no type 1 bursts were detected from the Rapid Burster). There was an interesting anti-correlation between burst duration and mean peak burst flux; the higher the burst flux, the shorter was its duration (I do not recall that this has previously been reported).

The observations were made in collaboration with Luigi Stella, Arvind Parmar, Nick White, and Jan van Paradijs (Stella et al. 1985). Luigi is not present at this meeting, and he has asked me to present some of our results. [In this paper, I will only describe some of the salient features; I will not present the figures that I did show at the meeting. A paper, presently in preparation, will contain a complete description and figures (Stella et al. 1986; see also the EXOSAT Calendar September 1986; Stella 1985,1986)]. I will first describe the QPO characteristics observed in the type 2 bursts, and then those observed in the persistent emission between these bursts.

1.2. QPO in the Type 2 Bursts

QPO were observed in many (not all) type 2 bursts. The **mean** centroid QPO frequency, ν, in the bursts ranges from ~2-5 Hz; it is strongly anti-correlated with the **mean** peak burst flux, I, [$\nu \propto I^{(-0.9\pm0.1)}$]. During the type 2 bursts, the peak burst flux can vary (up to ~20%), and the centroid QPO frequency can also change. This change can be correlated, or anti-correlated, or not correlated at all with the variable peak burst flux.

1.2.1. Strength of QPO and LFN. The strength of the QPO is the highest (rms variation ~20%) when the **mean** peak burst flux, I, is relatively low (400 cts/sec, 1-15 keV); it decreases when I increases. For values of I between ~1000 and ~1200 cts/sec, the strength varies between ~3% and ~10%. Tawara et al. (1982) observed in 2 of 63 type 2 bursts a strength of ~30%.

The strength of the low-frequency noise (LFN) is relatively low (up to a few %). As an example, **when the QPO strength during a 12-min type 2 burst was ~21%, the strength of the LFN in the range 0.0039 Hz to 0.3 Hz was only ~1.4%.**

1.3. QPO in the Persistent Emission

In between the type 2 bursts, a relatively strong (~200 cts/sec; for comparison with type 2 bursts, see above), and variable "persistent" flux is observed. As previously observed with the SAS-3 Observatory, this persistent flux declines substantially just before burst onset, and just after a burst has occurred (Van Paradijs, Cominsky and Lewin, 1979; Marshall et al. 1979). QPO is, in general, detected in the persistent emission when the burst intervals are relatively short (~600-1000 sec); it is not observed when the burst intervals are in excess of ~1500 sec. The QPO centroid frequency between bursts typically changes from ~4 Hz after a burst, when the persistent emission has just come out of its few-minute decline, to ~2.5 Hz, just before the next decline which is then followed within ~1 min by another type 2 burst.

There are times, particularly when the persistent emission shows flare-like events, that the QPO centroid frequency is anti-correlated with the persistent flux; but no general relation exists. There is, however, a clear correlation between the spectral hardness of the persistent emission (~4-10 keV/~1-4 keV) and the QPO frequency; the higher the hardness ratio, the higher is the frequency.

1.3.1. QPO Strength. The strength of the QPO in the persistent emission can be as high as ~30%. This is higher than what we observed in the type 2 bursts but comparable to what Tawara et al. (1982) observed in 2 of 63 type 2 bursts (see above).

1.3.2. Fundamental and First Harmonic. During a particular ~4-min interval, starting ~6 min before the onset of a type 2 burst, and ~12 minute after the end of the previous burst, two QPO frequencies of ~0.44 Hz and ~0.88 Hz were simultaneously observed. Their strength (rms variation) was ~24% and ~14%, respectively. It is likely that they represent the fundamental and first harmonic of a quasi-periodic variability in the persistent flux.

1.4. Different Origins of QPO?

The complexity in QPO characteristics in the Rapid Burster is unlike that in any other source; the mechanism responsible for its QPO may be different. It is also possible that the simultaneously observed ~0.44 Hz and ~0.88 Hz QPO have a different origin than the ~2-5 Hz QPO observed in both the persistent emission and in the type 2 bursts.

2. Models vs Observations - a Brief Review.

2.1. QPO in Cataclysmic Variables

Quasi-Periodic Oscillations are commonly observed in the optical flux (in a few cases also in X rays) of dwarf novae in outburst (dwarf novae are accreting white dwarfs; for reviews see e.g., Robinson and Nather 1978; Patterson 1981; Cordova and Mason, 1983). The timescale of these oscillations ranges from ~10-10^3 sec (frequency ~1 mHz to 0.1 Hz) and the coherence ranges from a few oscillations up to ~10^5 oscillations. QPO with very different coherence can be observed simultaneously at two frequencies. The strength of the optical oscillations is typically less than 1%. Many models have been proposed to explain these oscillations. Not one alone can explain the whole range of complex phenomena; it is almost certain that more than one mechanism is at work.

It is not surprising that the recent models on high-frequency QPO observed in the bright LMXB reflect some ideas put forward earlier for optical QPO in the Cataclysmic Variables. In scaling the geometry of an accreting white dwarf to that of an accreting neutron star, it is not too difficult to imagine a frequency increase by a factor ~10^{2-3}.

2.2. Long-Period QPO in LMXB

Before I discuss some of the current models for the high-frequency QPO in the bright LMXB, I want to mention that long-period QPO of ~10-10^3 sec have also been observed in several X-ray binaries. The QPO spectrum can be softer as wel as harder than the mean source spectrum. The fraction of the modulations in the flux (thus the strength of the QPO) can be enormous (typically ~50%). I list here only those cases that I am aware of in sequence of increasing frequency from ~1 mHz to ~2 Hz (1626-67 Joss, Avni and Rappaport 1978; Li et al. 1980; Cyg X-3 Van der Klis and Jansen 1985; GX 349+2 Matsuoka 1985; Her X-1 Voges et al. 1985; 1820-30 Stella, Kahn and Grindlay 1984;

GX 339-4 Maejima et al. 1984). Perhaps the 1.5-h oscillations observed by Langmeier et al. (1985) in GX 17+2 are also quasi-periodic; this would then extend the range of long-period QPO in LMXB up to periods of ~5×10^3 sec. I suspect that these long-period QPO have a different origin than the short-period QPO. However, it is unclear as yet where the dividing line is (perhaps somewhere between 0.01 and 1 Hz).

2.3. QPO Models

The models that I will now discuss have been proposed to explain some of the recent observations of high-frequency QPO in LMXB (Alpar and Shaham 1985a,b; Berman and Stollman 1985; Lamb et al. 1985; Lamb 1986; Hameury, King and Lasota 1986; Boyle, Fabian and Guilbert 1986; Morfill and Truemper 1986a,b). It is interesting to look at the evolution of some of them in historical perspective. The excitement, and activity started with the discovery of the intensity dependent QPO in GX 5-1 in early 1985 (Van der Klis et al. 1985a,b). The centroid frequency of the QPO, ν, was linearly related to the observed source intensity, I, ($\nu \approx 1.9\times10^{-2} I - 25$ Hz) over the observed range of I from about 2400-3400 cts/sec (1-18 keV). No one paid much attention to this linear relation then, and not now, and even though we mention the linearity in our paper, we do not give it quantitatively (Van der Klis et al. 1985b). Our data can also be fit by a power-law dependence ($\nu \approx 6.9\times10^{-6} I^{1.9}$ Hz). The observed exponent (which I will designate α) led Alpar and Shaham to the idea that QPO could be the result of a beat phenomenon, as earlier suggested by Warner (1983) for optical QPO in cataclysmic variables. Another striking relation was present between the strength of the QPO and that of the low-frequency noise (LFN); the two went "hand in hand" (Van der Klis et al. 1985b).

2.3.1. The Bath Model. Before I expand on the beat frequency idea, I want to remind you of a model suggested 13 years ago by Geoffrey Bath to explain optical QPO in cataclysmic variables (Bath 1973). He suggested that the QPO frequency was that of the Kepler frequency of matter orbiting a magnetized white dwarf at the magnetopause (inner edge of the accretion disk). This idea can be adopted to magnetized accreting neutron stars in an effort to explain the observed high-frequency QPO in X rays; I will refer to this hereafter as "the Bath model". The radius of the inner edge of the accretion disk, r, depends on the mass and radius of the neutron star, on the magnetic dipole field strength at the surface of the neutron star, and on the mass transfer rate $\dot{M}$ at that radius (see Lamb, Pethick and Pines 1973). Combining the relation between r and $\dot{M}$ with Kepler's law, and assuming that the Kepler frequency, ν_K, equals the QPO frequency, ν, (Bath model) one can easily find that

$$\nu \propto \dot{M}^{3/7} \qquad (1).$$

If we now make the assumption that $\dot{M}$ depends linearly on the observed broad-band X-ray intensity, I, we find that the observed QPO frequency, ν, should be proportional to I to the power 3/7, thus:

$$\nu \propto I^{3/7} \qquad (2).$$

This, however, was not observed; α was ~2, and not 3/7 (Van der Klis et al. 1985a,b).

2.3.2. The Beat Frequency Model. In the beat frequency model (Alpar and Shaham 1985a,b), the observed QPO frequency is the difference between the Kepler frequency, ν_K, and the rotation frequency, ν_n, of the neutron star

$$\nu = \nu_K - \nu_n \qquad (3).$$

If again the assumption is made that the mass transfer rate, $\dot{M}$, at the magnetopause depends linearly on the observed broad-band X-ray intensity, one finds that

$$\alpha = 3\nu_K/7\nu \qquad (4).$$

Combining eqs. 3 and 4 leads to:

$$\nu_n = \nu(7\alpha/3 - 1) \qquad (5).$$

If, as an example, we take an approximate average value of 30 Hz for the observed QPO frequency, ν, in GX 5-1, then, with $\alpha \approx 2$ (as observed), $\nu_K \approx 140$ Hz (eq. 4), and $\nu_n \approx 110$ Hz (eq. 5). Assuming a mass for the neutron star of 1.4 $M_\odot$, with Kepler's law we can then also find the radius of the inner edge of the accretion disk (here ≈55 km). If, in addition, one assumes a radius for the neutron star (e.g., 10 km), and one estimates the mass transfer rate at the magnetopause (this can be done from an estimate of the distance to the source, and from the observed broad-band X-ray intensity), one also finds the magnetic dipole field strength, B, at the surface of the neutron star, using the equations given by Lamb, Pethick and Pines (1973). For GX 5-1, one finds $B \approx 6 \times 10^9$ G.

As we just saw, in the case of GX 5-1, the beat frequency model (Alpar and Shaham 1985a,b), leads to the neutron star rotation period, and to its magnetic dipole field strength. These results were very pleasing as they fitted well into an existing evolutionary scenario in which the neutron stars in the bright LMXB are spun up by accretion and form the progenitors of msec binary radio pulsars (see e.g., Smarr and Blandford 1976; Van den Heuvel 1981; Radhakrishnan 1981; Srinivasan and Van den Heuvel 1982; Alpar et al. 1982; Radhakrishnan and Srinivasan 1982; Webbink, Rappaport and Savonije 1983; Taam 1983; Joss and Rappaport 1983; Paczynski 1983; Savonije 1983).

Problems? If the beat frequency idea is correct, it is puzzling that we do not observe in our GX 5-1 data ~110 Hz **coherent** X-ray pulsations (however, see Lamb et al. 1985, and Lamb 1986). The absence of coherent pulsations may not be the only problem. A few months after QPO were found in GX 5-1, they were also discovered in Sco X-1 (Middleditch and Priedhorsky 1985, 1986; see also Priedhorsky et al. 1986; Van der Klis et al. 1986). Here the observed QPO frequency was **anti-correlated** with the observed source intensity ($\nu \propto I^{-0.6}$). Thus, α was negative. As long as we make the above assumption that $\dot{M}$ is linearly proportional to the observed X-ray intensity, α can not be negative. This can easily be seen as follows. Any increase in I will be associated with an increase in $\dot{M}$. This leads to a smaller radius of the magnetopause, and thus to an increase in the Kepler frequency. If the Kepler frequency goes up, the QPO frequency will also go up (see eq. 3).

Introduction of the β parameter. Lamb et al. (1985) do not assume that the observed X-ray intensity is linearly proportional to $\dot{M}$, but rather

$$I \propto \dot{M}^{\beta} \qquad (6).$$

Here β can have all values between $-\infty$ and $+\infty$, as can easily be seen. Suppose there is no change in $\dot{M}$, but there is, e.g., a minute decrease in the observed X-ray intensity as the result of a small increase in absorption along the line of sight; β would then be $-\infty$. If the absorption were to decrease, β would become $+\infty$; β can have all values in between. For "n-fold symmetry" (Lamb et al. 1985; see also below) eq. 3 becomes

$$\nu = n(\nu_K - \nu_n) \quad [n=1,2,3,......] \qquad (7).$$

With the introduction of β, we find for the beat frequency model

$$\alpha = 3n\nu_K/7\beta\nu \qquad (8).$$

For n=1, and $\nu_K = \nu$ (Bath model), we find

$$\alpha\beta = 3/7 \qquad (9).$$

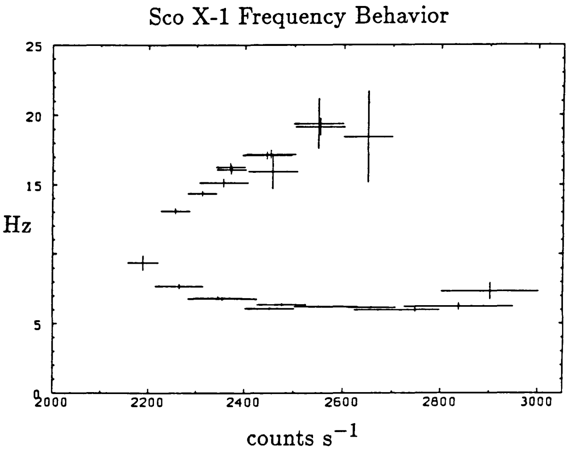
Combining eqs. 7 and 8, the beat frequency model leads to

$$n\nu_n = \nu(7\alpha\beta/3 - 1] \qquad (10).$$

The rotation frequency of the neutron star plays no role in the Bath model. The latter is mathematically equivalent to the beat frequency model with $n\nu_n=0$, and $\alpha\beta=3/7$ (eq. 10).

With the introduction of the β parameter (with $\beta\neq1$) the beat frequency model can obtain any value for the rotation frequency of the neutron star. This can best be illustrated with an example. Priedhorsky et al. (1986) found in Sco X-1 a "6-Hz QPO branch" which was anti-correlated with the source intensity ($\alpha\simeq-0.6$), and a "15-20 Hz branch" which was correlated with the source intensity ($\alpha\simeq+3$) (see also Van der Klis et al. 1986). Their results are shown in the figure below. With the observed values for ν and α (using eq. 10), we can now find values for β to obtain any neutron star rotation rate. For instance for a rotation frequency $n\nu_n=1000$ Hz, β would have to be ~+9 in the 15-20 Hz branch, and ~−120 in the 6-Hz branch. For a rotation rate ($n\nu_n$) of 100 Hz, the corresponding values for β would have to be ~+1, and ~−13, respectively. The rotation rate can also be zero (this is mathematically equivalent to the Bath model). Then, the values for β would have to be ~+0.14, and ~−0.7, respectively (here $\alpha\beta=3/7$). Near the apex of the "curve" (see figure below), $\alpha=\pm\infty$, (observational fact). If at the same time $\beta=0$ (i.e., the mass transfer rate changes, but no simultaneous source intensity change is observed), the product $\alpha\beta$ becomes undetermined, and this is consistent with any neutron star rotation frequency.

In this context it is interesting to mention that Priedhorsky et al. 1986 (see also Priedhorsky 1986) suggest that in "tracing" the curve of the figure below in a clockwise direction, there is a continuous monotic increase in the mass transfer rate which, however, is not reflected in a continuous increase in the **observed** broad-band X-ray intensity. With increasing mass transfer rate, the **observed** intensity at first decreases (6-Hz branch), and then increases (15-20 Hz branch). If this suggestion is correct, it would mean that near the apex, where the two branches meet, $\beta=0$.



Centroid QPO frequency, ν (in Hz), vs. the 8-20 keV X-ray intensity, I (in cts/sec), observed for Sco X-1 with EXOSAT. In the upper QPO branch (15-20 Hz) the frequency and source intensity are correlated; $\nu\propto I^{+3}$. In the lower branch (~6 Hz), the QPO frequency is anti-correlated with I, here $\nu\propto I^{-0.6}$. This figure is from Priedhorsky et al. 1986.

In my opinion, the main reason for the early rejection of the Bath model in favor of the beat frequency model is no longer valid. With the introduction of β ($\neq1$), which seems entirely reasonable, the product $\alpha\beta$ counts, and no longer α alone. In the Bath model $\alpha\beta=3/7$, and any observed value of α is allowed (thus also $\alpha\simeq2$ as observed for

GX 5-1, as long as $\beta \simeq 0.21$). In the absence of knowledge of β (β can vary on a timescale of minutes), we are at a loss (however, see Priedhorsky 1986). **Obviously, this does not mean that the beat frequency model is incorrect.** It is too early to decide (see also Hasinger, 1987, and the note added at the end of my text).

A specific beat frequency scenario has been proposed by Lamb, Shibazaki, Alpar and Shaham (1985) (see also Van der Klis et al. 1985b; Berman and Stollman 1985; Lamb 1986). They suggest that the beat phenomenon is the result of blob formation at the inner edge of the accretion disk. The matter in the blobs is gradually stripped off by interaction with the magnetic field which is anchored into a spinning neutron star. The matter will then reach the surface of the neutron star in a quasi-periodic fashion with a frequency equal to the difference between the (variable) Kepler frequency of the blobs and the (fixed) rotation frequency of the neutron star (see eq. 3) [or n times that for n-fold symmetry (see eq. 7)]. While a blob is "milked" the X-ray flux oscillates (producing QPO), and the mean X-ray flux is temporarily increased. The latter gives rise to low-frequency noise (LFN). The model can be represented by oscillating "shots". The oscillatory part of the shots determines the QPO characteristics; the envelopes of the shots determine the characteristics of the LFN. The blobs are produced at random times, and with a random equatorial azimuthal distribution. For a sufficiently large number of blobs, the "crests" of the oscillations, produced by one blob, will always coincide (or nearly so) with the "valleys" of those produced by others, and both the QPO and the associated LFN will disappear.

In this scenario, LFN is **"a logical consequence"** of the QPO, and one would expect to observe strong LFN whenever strong QPO are observed. This was the case in GX 5-1 where the QPO and the LFN strength went "hand in hand". However, in later observations of e.g., Sco X-1 and the Rapid Burster this was not the case (sect. 1.2; Stella 1985,1986; Stella et al. 1986; Van der Klis et al. 1986). Fred Lamb kindly pointed out to me (see also Lamb 1986, and Shaham 1987) that one can adjust the mathematics of the shots so that the blobs oscillate more or less in unison (crests from one blob support crests from other blobs). This could give strong QPO in the near abscence of LFN. It remains to be seen, however, whether this mathematical adjustment is physically meaningful.

2.3.3. Other Models. I will now discuss some other models. They will not get as much attention as the model proposed by Alpar and Shaham (1985a,b). This does not mean that I favor their model. It merely reflects that it has been around longer and evolved (Lamb et al. 1985; Lamb 1986) as the observations revealed more complex behavior and richness in the QPO, and LFN. I thought it was worthwhile to discuss some aspects of this evolution.

Morfill & Truemper (1986a) suggested a magnetospheric beat frequency model in a heavily obscured binary. The supersonic stirring of the disk by an inclined magnetic field causes shock waves which interact with disk inhomogeneities (plasmoids) in Keplerian rotation. The plasmoids are hotter than their environtment. This results in a quasi-periodic signal at the beat frequency (eq. 3). Unlike in the beat frequency model discussed above, here the QPO signal does not come from the surface of the neutron star but from the plasmoids in the magnetopause (self-luminous plasmoid model). Thus the available energy in the QPO is dictated by the radius of the magnetopause. If the latter were e.g. ten times that of the neutron star, the maximum available energy (to produce QPO) would be ~10% of the total X-ray flux (for larger radii it would be lower, for smaller radii larger). The QPO mechanism could not be 100% efficient (see Lamb 1986). "Self luminous" models like this one, can therefore perhaps explain QPO with a modest strength, but it is hard to see how they could explain the high percentages observed in e.g., GX 5-1 (up to ~6%), Sco X-1 (up to ~8% at high energy X rays), and the Rapid Burster (up to ~30%). [For references see above].

In a later version, Morfill and Truemper (1986b) point out that one may expect the formation of large vortices in the disk flow (near the magnetopause), and that vortex shedding (perhaps associated with a characteristic Strouhal frequency) is likely to occur. They show that under certain conditions, and with a constant Strouhal number of ~1.3, the QPO frequency could be about twice the Keplerian frequency (i.e., $\sim 2\nu_K$). They also mention that other phenomena such as frequency halving or doubling may add further complexity. They point out that the observed QPO frequencies could perhaps also be due to the single Keplerian frequency of the plasmoids and/or to a beat frequency.

These are all versions of "self-luminous" models, and my comments regarding the limited available energy for the QPO should also be valid here. The authors, however, allow for the possibilty that the QPO are the result of shadowing of the central source by hot cocoon gas, in which case the limitation in available energy is not a problem (see sect. 2.4).

In their closing comments, Morfill and Truemper (1986b) also suggest that the interaction of the plasmoids with the shocks (the latter are revolving with the neutron star rotation frequency) may bring accretion disk material into co-rotation, and thus making accretion along the field lines onto the polar caps feasible. If that happens, the QPO emission comes from the neutron star surface with a beat frequency (see eqs. 3 and 7); this scenario has similarities with that proposed by Lamb et al. (1985) (see also Lamb 1986).

Hameury, King and Lasota (1985) proposed a scenario which does not require the presence of a magnetopause. The QPO are the result of hot spots rotating in the boundary layer where the accreting matter settles onto the surface of a "slowly" rotating (with a period of order ~1 sec) neutron star. They suggest that transient magnetic fields are generated due to turbulent dynamo action, and that the local hot spots are heated by conduction due to these magnetic fields. QPO are then the result of repeated occultations of the hot spots when they rotate out of our line of sight to the "back side" of the neutron star. The low-frequency noise results from the lifetime of the hot spots, and from those spots that are never occulted due to their high lattitude. The authors predict that the QPO spectrum is that of a blackbody with a radius less than that of the neutron star. There is some growing evidence that the QPO spectra are indeed blackbodies for Cyg X-2 (Hasinger, 1987), and Sco X-1 (Van der Klis et al. 1986). A blackbody spectrum, however, is not unique to this model.

The "available" frequencies in this model range all the way from ~1 Hz (at the bottom of the boundary layer, rotating with the neutron star frequency) to $\sim 10^3$ Hz (at the very top of the boundary layer rotating with the Keplerian frequency). If this scenario were operating, it is puzzling why the observed QPO frequencies vary only in such a limited range (e.g., in GX 5-1 by a factor of ~2), and why the width of the peaks in the power spectra of most QPO sources are so narrow (typically ~10% to ~30%). Since here the LFN is a logical consequence of the QPO, it may also be difficult to explain those cases of observed near absence of LFN in the presence of strong QPO (see sect. 1.2, and the end of sect. 2.3.2). It is also unclear whether the hot spots could contain such a high fraction of the available gravitational potential energy to explain the observed high strength of QPO (typically ~5% rms variation, but up to ~30% in the Rapid Burster, see sects. 1.2 and 1.3).

A particular hot spot would have to appear and disappear (occultation) at least three or four times to produce the observed QPO. The QPO with a fundamental frequency of ~0.44 Hz in the Rapid Burster (sect. 1.3.2) would thus require a lifetime of the hot spots of at least ~10 sec. According to Jean Paul Lasota (private communication), the lifetime of a hot spot is probably less than a few seconds. Thus, if this is so, the very low-frequency QPO could not be explained with this "sun spot" scenario. It seems quite possible that more than one mechanism is responsible for the various "kinds" and different characteristics of the QPO (see also sect. 2.2, and Hasinger 1987), and it would be somewhat naive to expect that one model could explain them all.

Boyle, Fabian and Guilbert (1986) proposed that the QPO are produced by a hot ($>10^7$ °K) accretion disk corona. X rays produced at the central source (the neutron star) scatter off oscillating disturbances in this corona near the inner disk. The oscillations are in a direction perpendicular to the disk plane (disk oscillations); they have a frequency approximately equal to the local Keplerian frequency. Thus, QPO frequencies of ~100 Hz and ~1 Hz, would correspond to an effective scatter radius of $\sim 8\times10^4$ m (~8 stellar radii) and $\sim 1.6\times10^6$ m (160 stellar radii), respectively. No magnetic field, and no neutron star rotation are required.

The X rays scatter off the $\tau \simeq 1$ surface. Since the observed peaks (QPO) in the power spectra have widths of typically ~10 to ~20%, a very restricted range of radii of this scatter surface is required. The spread in the radii of the effectively contributing part of this surface (as seen from Earth) should be no larger than ~30%. Thus this scatter surface must be very steep and well localized. It is not sufficient that the disk oscillations cause this surface to move closer to, or farther away from, the neutron star by ~30%, as this would not modulate the scattered X rays sufficiently to produce the observed oscillations. The scatter surface should more or less "come and go" (with the frequency of the disk oscillations) in order to obtain a strong modulation in the scattered X rays. It should act as a "wall" that rises and falls at the required frequency. The authors predict that those systems seen at low inclinations are favored (no QPO should be seen from eclipsed systems).

The fraction of X rays that scatter off the accretion disk coronae in 1820-37 and 2129+47 is no more than ~10% (Keith Mason and Nick White, private communication). If this number is typical for LMXB, it is very hard to see how the disk oscillations could produce the high strength of QPO (typically ~5% rms variation, but up to ~30% in the Rapid Burster, sects. 1.2 and 1.3). If the modulation efficiency (of the scattered X rays) were as high as ~10%, one would expect to observe a modulation in the total X-ray signal (scattered and non-scattered) of only ~1%. If the central source were obscured, the situation would be different, and the observed percentage of modulation would be much higher since then only the scattered X rays are seen. This, however, is not the case for most (if not all) sources in which QPO have been detected (the sources are very bright).

The authors appreciate the problems and suggest that non-linear effects might help to localize the $\tau \simeq 1$ surface. Such non-linear effects are unexplored. The physics is not understood, and so far it appears to be only an interesting mathematical exercise until more theoretical work is done.

2.4. Occultation Models

Some of the ideas as put forward by Morfill and Truemper (1986a,b) may work if the plasmoids are not self luminous (see above) but occult the central source. Similarly, the disk oscillations (Boyle, Fabian and Guilbert 1986) could produce a high degree of modulation if the neutron star is obscured by the oscillating disturbances. Van der Klis et al. (1986) (see also Van der Klis 1987) show that certain occultation models can explain the absence of LFN in the presence of strong QPO. Occultation models do not suffer from a lack of available energy for the QPO. However, they probably require that the systems that exhibit QPO are seen at a rather large inclination, and it is puzzling why that would be the case for so many bright low-mass X-ray binaries.

3. Concluding Remarks

As of today (May 29, 1986) we do not yet know what causes the QPO, not even whether they are magnetospheric in origin (see note added below). It appears that none of the proposed scenarios can alone explain the richness and complexity in the high-frequency quasi-periodic X-ray oscillations now observed in about eight bright low-mass X-Ray binaries (above references; Stella 1985; Lewin and Van Paradijs 1986; Van der Klis 1986; and references therein). However, some of the proposed ideas could well be relevant to some aspects of the QPO. In any case it is likely that more than one mechanism is at work.

In the light of this ignorance, I would like to finish with a humorous quote from Harlow Shapley which was brought to my attention by Ed Chupp (1984).

> A hypothesis or theory is clear, decisive and positive but it is believed by no one but the man who created it. Experimental findings, on the other hand, are messy, inexact things which are believed by everyone except the man who did the work.
>
> Harlow Shapley

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Note added

Guenther Hasinger (1987) has shown at this meeting that in the case of Cyg X-2 the rapid variabilty in high-energy photons lags that of the low-energy photons by several msec; the time lag is smaller when the QPO frequency is larger. He suggests that Comptonization is responsible for the time lag. For a delay of ~3 msec, and a Compton optical depth of ~5, the size of the scattering cloud would be ~170 km. At that radius the Kepler frequency of matter orbiting the neutron star is ~20 Hz (as observed in Cyg X-2). When the Compton scattering cloud moves closer to the neutron star the QPO frequency would become larger, and the time lag smaller. Guenther's new, and very interesting findings are in general support of the Bath model which explains the QPO frequencies in terms of the Keplerian frequencies of orbiting matter at the magnetopause; this model provides no information on the rotation frequency of the neutron star (see text).

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