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CHAPTER V

TRYING TO UNDERSTAND QPO: A REVIEW

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1. Introduction

In this chapter I will give a review of the models that have been proposed so far to explain the quasi-periodic oscillations (hereafter QPO) observed in some low-mass X-ray binaries (see Van der Klis, 1986a, for a list of all sources). These models will be discussed against the background of some key characteristics of the observations of GX 5-1, Cyg X-2 and Sco X-1 which have, until now, been observed in most detail. As the presence of QPO is inferred from the power spectra of the intensity variations of the X-ray source, I will give a brief introduction to these spectra in section 2, which will be worked out in more detail after the basic properties of the models have been discussed in, section 4. In section 3 a brief review of the observations is given.

2. Power spectra

The existence of quasi-periodic oscillations in an X-ray source is inferred from its power spectrum, $P(v)$, defined by $P(v) = F(v) F^*(v)$, where $F(v)$ is the Fourier transform of the X-ray intensity as a function of time [i.e., $I(t)$], $F^*(v)$ its complex conjugate, and $v$ the frequency. The quantity $F(v)dv$ gives the amplitude of the harmonic contributions comprising the signal $I(t)$, within the frequency range from $v$ to $v + dv$. Hence, $|F(v)|^2$ serves as a spectral amplitude density and its square $|F(v)|^2 = F(v) F^*(v)$ (i.e., Parceval's formula) is the power per unit frequency interval.

For each feature in the power spectrum between $v = v_1$ and $v = v_j$ the power $P_{ij}$ is given by

$$P_{ij} = \int_{v_1}^{v_j} P(v) \, dv$$

(1)

Given an intensity $I(t)$ for which the mean value is $<I(t)> = I_0$, the power in the zero-frequency component of the power spectrum is $P_0 = I_0^2$. Quantities often used in the literature on QPO, to express the strength of a feature in the power spectrum are:
a: the \textit{r.m.s. fractional intensity variation}, $\gamma$, defined by

$$\gamma_{1j} = \left( \frac{P_{1j}}{P_0} \right)^{1/2}$$

b: the \textit{fractional modulation}, $m$, defined as half the peak-to-peak intensity variation of a sinusoid of equivalent power, divided by $I_0$. For a sinusoid given by $I(t) = A \sin(2\pi v_0 t)$, the power is given by $P_{1j} = A^2/2$. Therefore,

$$m_{1j} = A/I_0 = 2^{1/2} \gamma_{1j}$$

Typical power spectra from, for example, GX 5-1 can be seen in Van der Klis et al. (1985). The two features that are of particular interest and which have to be explained by any theoretical model are the low frequency noise (hereafter denoted by "LFN") - sometimes referred to as red noise - and the "QPO"- peak. The LFN indicates that stochastic variations are present in the intensity of the X-ray source, of which the slowest ones have the largest amplitude (i.e. $dP(v)/dv < 0$). The quasi-periodic oscillations manifest themselves as a broad peak with FWHM $\Delta v_{QPO}$ in the power spectrum, centered around the centroid frequency $v_{QPO}$. As pointed out above, the area under the peak represents the power in the quasi-periodic oscillations.

There are several ways to produce such a broad peak in the power spectrum (see e.g., Van der Klis, 1986a). However, the power spectra cannot distinguish between these because the phase information in the signal is lost. In most of the theories discussed below the signal $I(t)$ is thought to consist of finite wave trains of $n$ oscillations. If each wave train has a length $\Delta t$, then the power spectrum will have a broad peak of width $\Delta v \sim 1/\Delta t$, centered around the basic frequency, $v_0$, of the oscillation. The number of oscillation cycles in each wave train is then $n \sim \Delta t/P$, where $P$ is the period (i.e. $P = 1/v_0$) or $n \sim v_0/\Delta v$. The larger $n$ is, the more coherent the oscillations are. In the observation of QPO the value of $n$ is typically of order 1 and the coherence is, therefore, low. In contrast to this, the power spectra of X-ray pulsars contain a sharp delta-peak at the rotation frequency of the neutron star and $n$ is very large.

3. \textit{Key observations}

The basic properties of QPO sources that can be observed are the count rate or intensity, $I(t)$, the QPO-frequency, $v_{QPO}$, the power in the QPO-peak and in the low frequency noise, and the energy spectrum of the source, often given in terms of a hardness ratio. Some of these quantities are correlated with one
another, and this has been important for the development of the theoretical models. As mentioned above, I will only give a brief review of these correlations as observed in GX 5-1, Cyg X-2 and Sco X-1. For the details of the observations I refer to van der Klis et al. (1985) and van der Klis (1986a) for GX 5-1; Hasinger et al. (1986) and Hasinger (1986) for Cyg X-2 and Middleditch and Friedhorsky (1985) and van der Klis et al. (1986) for Sco X-1.

3.1. The correlation between QPO-activity and spectral behaviour

In the sources mentioned above the hardness ratio versus intensity diagram consists of basically two branches. The hardness ratio is the ratio between the count rate of the source in a high-energy band and a lower energy band. The precise definition of these bands depends on the instrument used in the observation. On different branches the sources show a different QPO behaviour.

In both GX 5-1 and Cyg X-2 there is a "horizontal" branch on which the hardness ratio is nearly constant as a function of intensity and a "normal" branch on which the hardness ratio increases monotonically with intensity (Branduardi et al., 1980; Shibazaki and Mitsuda, 1983).

GX 5-1 shows intensity correlated QPO (20 Hz < $v_{QPO}$ < 36 Hz) when on the so-called "horizontal" branch, and perhaps low-frequency QPO ($v_{QPO}$ ∼ 5 Hz) when on the normal branch. Cyg X-2 shows intensity correlated QPO (28 Hz < $v_{QPO}$ < 45 Hz) when on the horizontal branch and intensity independent QPO (of lower frequency, nl. $v_{QPO}$ ∼ 5 Hz) when on the normal branch. The two branches for these two sources imply two different spectral states and the QPO frequency changes abruptly from one state to the other.

For Sco X-1 the correlation between spectral and QPO behaviour is different. This source exhibits periods of active flaring and periods of quiescence and a gradual transition between the two. When active, Sco X-1 shows QPO (10 Hz < $v_{QPO}$ < 20 Hz) in the intervals between flares; the source is then on the so-called "active" branch of the hardness versus intensity diagram. When in quiescence the source shows QPO of lower frequency ($v_{QPO}$ ∼ 6 Hz) and is also on a different branch in the hardness versus intensity diagram (i.e., the quiescent branch). In contrast to GX 5-1 and Cyg X-2 there is a gradual transition in QPO frequency between the two branches.

3.2. The correlation between $I(t)$ and $v_{QPO}$

When they are on the "horizontal" branch in the hardness versus intensity diagram both GX 5-1 and Cyg X-2 show a strong correlation between the observed intensity and the QPO-frequency. However, for the low-frequency QPO observed from Cyg X-2, when this source is on the normal branch, there is no clear
intensity correlation.

In Sco X-1 there is a different correlation between I and v_{QPO} for each state the source is in. When active, QPO is observed in between the flares and the frequency is correlated with intensity. When the source is in quiescence the QPO frequency is lower and anticorrelated with intensity. When Sco X-1 switches from the active to the quiescent state (sometimes referred to as the intermediate state) the frequency changes between 6 and 20 Hz with no single relation to the intensity.

3.3. The correlation between QPO-activity and LFN

Both GX 5-1 and Cyg X-2 show LFN of strength similar to that of the QPO. In GX 5-1 the power in the QPO-peak and in the LFN are roughly equal, and both are anticorrelated with intensity in a similar way. For Cyg X-2 the power in the LFN increases for increasing intensity, whereas that in the QPO-peak decreases. However, in Sco X-1 the strength of the LFN is less than that of the QPO.

3.4. The correlation between black-body luminosity and V_{QPO}

When the X-ray spectrum of Sco X-1 is decomposed into two spectral components (i.e., a black body component thought to originate from the surface of the neutron star and a component thought to originate from the disk; see e.g., White et al. (1986) and Mitsuda et al. (1985)), it is seen that over the whole range of states that Sco X-1 can be in, the QPO-frequency seems to be simply correlated with the luminosity of the black-body component. Also for Cyg X-2 the relation between the luminosity of the black-body component and v_{QPO} is much simpler than that with the total intensity of the source.

3.5. Observed time delay for QPO

Hasinger (1986) found from a cross-correlation between the light curves of Cyg X-2 - when the source was on the horizontal branch - in a high-energy band (4.5 - 17 keV) and in a low-energy band (1.0 - 4.5 keV), that there is a time lag for the hard photons with respect to the soft ones. This time lag is smaller for higher QPO-frequencies.

The delay is also found for the QPO in GX 5-1 (Van der Klis, 1986b). However, in this source the value for the delay is smaller (~ 0.5 to 1 ms in GX 5-1 versus ~ 1.5 to 4 ms in Cyg X-2).

4. Theoretical models

It is generally assumed that low-mass X-ray binaries consist of a neutron star that is accreting matter from a normal companion star, via an accretion
In my discussion of the theoretical models that have been proposed so far to explain the QPO observed in some of these systems I will make a distinction between so-called "magnetospheric models" and other models. The magnetospheric models are based on the assumption that the neutron star has a magnetic field that is able to control the manner in which the accreted gas flows towards the stellar surface. In these models the observed frequency is then related in some way to the Kepler frequency of matter moving in the disc at the magnetospheric radius, \( r_A \) (see below). In the other type of models proposed, the neutron star does not necessarily have a magnetic field and the QPO-frequency is not necessarily related to the Kepler frequency.

4.1. Magnetospheric models

The standard Alfven or magnetospheric radius, \( r_A \), is usually derived for spherical accretion, since in that case a simple relation exists between the accretion rate \( \dot{M} \) and \( r_A \). (For the case of disk-accretion see Ghosh and Lamb (1979)). We expect that the field will begin to control the accretion flow when the magnetic energy density becomes comparable with the total kinetic energy density of the gas. Therefore, \( r_A \) is implicitly given by \( B^2 (r_A) / 8 \pi = 1/2 \rho (r_A) v^2 (r_A) \). For steady, transsonic, spherical flow at nearly free-fall velocity the density and velocity are given by \( \rho (r) = \dot{M} / 4 \pi r v^2 \) and \( v(r) = (2GM/r)^{1/2} \) respectively. For a supposed dipole magnetic field outside the neutron star, of magnitude \( B = \mu / r^3 \) at distance \( r \), the Alfven radius can then be written as

\[
  r_A = \left( \frac{\mu}{2GM} \right)^{1/7} \dot{M}^{2/7}
\]

Here \( \mu \) is the magnetic moment of the star.

It is usually assumed that the total X-ray luminosity \( L \) is related to \( \dot{M} \) via \( L = G M \dot{M} / R \). For a spherically emitting source \( L = 4 \pi d^2 F_d \), where \( d \) is the distance to the source and \( F_d \) the energy flux received at \( d \). The intensity or count rate \( I \) is related to \( F_d \) by \( F_d = I \langle E \rangle \), where \( \langle E \rangle \) is the average energy of the incoming photons. Hence, the intensity is simply related to \( \dot{M} \) as \( I = \alpha' \dot{M} \), where \( \alpha' = GM/4 \pi d^2 \langle E \rangle \). However, as pointed out by Lamb et al. (1985), in low-mass X-ray binaries it is possible that the observed luminosity is not simply proportional to the mass-accretion rate, for a number of different reasons: (i) the system may lose mass (and, consequently, energy); (ii) the geometry of the emission region may change (see chapter VII for a particular change of the emission region); (iii) rotational energy of the neutron star may be transferred to the disk via the magnetic field (Priedhorsky, 1986; chapter VIII). Therefore, in general, we may write
\[ I = a H^\beta \]  \hspace{2cm} (5)

where in principle the power \( \beta \) can vary from \(-\infty\) to \(+\infty\) (see also Lewin, 1986, for a discussion of the introduction of the parameter \( \beta \)). For the simple case mentioned above, \( \beta = 1 \) and \( a = a' \). From eq. (4) we then find a relation between the Alfvén radius and the observed intensity:

\[ r_A = \left( \frac{\frac{\mu a}{2 GM}}{1/7} \right)^{1/7} I^{-2/7\beta}. \]  \hspace{2cm} (6)

In the magnetospheric models for QPO proposed by Lamb et al. (1985), Morfill and Truemper (1986), and in chapter VI and VIII, it is assumed that the observed QPO-frequency is \( n \) times the difference between the Kepler frequency, \( v_K \), at \( r_A \) and the rotation frequency of the star, \( v_g \). (Usually \( n \) is set equal to 1). This difference is referred to as the beat-frequency and the models are usually called "beat-frequency models".

Alpar and Shaham (1985) were the first to suggest a beat-frequency model to explain the QPO observed in GX 5-1. The physical process responsible for this beat is due to the interaction at \( r_A \) between the accretion disk and the rotating magnetic field of the star. In the models put forward by Lamb et al. (1985) and in chapter VI this physical mechanism is "magnetic gating" or "modulated accretion". If it is assumed that the magnetic field of the star is able to control the accretion-flow and that the inner region of the disk, where the interaction with the magnetic field takes place, consists of regions or blobs of matter and if, furthermore, it is assumed that the interaction between these blobs of matter and the field depends on the phase angle \( \phi \) of the blobs in the accretion disk (e.g., due to an asymmetry in the field), then the accretion flow from these blobs will be modulated with \( n \) times the beat-frequency \( v_b = v_K - v_g \), assuming that the phase angle dependence of the interaction between the field and the matter has \( n \)-fold symmetry.

In the model by Morfill and Truemper (1986) the inner region of the accretion disk is stirred by the rotating magnetic field, which results in shocks that move through the disk with angular frequency \( \nu = v_g \) and interact with plasmoids (i.e., density inhomogeneities) that move with angular frequency \( \nu = v_K \). Due to this interaction the plasmoids are heated and start radiating. The radiation observed is modulated with \( n \) times the beat-frequency, again assuming \( n \)-fold symmetry.

In chapter VIII a model is presented in which the rotating magnetic field interacts with magnetic loops in the inner region of the disk. This interaction
leads to a transfer of rotational energy from the star to the disk, which can be emitted as X-rays. Again this interaction is modulated and may produce the observed QPO.

4.1.1. The expected power spectrum

In the models presented above, each \( n \)th blob or plasmoid contributes an amount \( I_n \), starting at time \( t_n \), to the total intensity. The latter is then

\[
I_{\text{tot}} = \sum_n I_n(t-t_n) 
\]

For reasons of simplicity, we now assume that the contribution from each blob or plasmoid is suddenly turned on and that this contribution to the intensity decays exponentially (i.e., takes the form of shots). Furthermore, we assume that each blob contributes a constant, and a modulated part to \( I_n \). For the latter we will take, again for reasons of simplicity, a simple cosine function. These specific assumptions will not alter the general conclusions but only the details of the power-spectra (see also discussion after eq. 13). Each \( I_n(t-t_n) \) can then be written as

\[
I_n(t-t_n; \phi_n) = \{1 + A \cos[2\pi \nu_0(t-t_n)+\phi_n]\} \theta(t-t_n) \exp\left(-\frac{(t-t_n)}{\tau}\right) 
\]

Here \( \phi_n \) is the phase angle or azimuthal position of each blob (at time \( t_n \) when it starts to contribute to the intensity) with respect to the direction of the magnetic field or the position of the shocks, where the interaction is most efficient. The function \( \theta(t) \) is the Heavyside function and is 0 when \( t < 0 \) and 1 when \( t > 0 \). We have normalized the constant contribution of each blob to 1, since we are only interested in the shape of the power spectrum. Then \( A \) is the modulation depth, which in general is the ratio of the modulated part over the constant part of the contribution of each blob. Since \( I_n \) is due to accretion or radiation of plasmoids it can never be negative, which leads to the constraint \( |A| < 1 \). In eq. (8) \( \tau \) is the decay time of the intensity of each blob and is basically its lifetime.

The Fourier transform of each \( I_n \), given in eq. (8), is

\[
F(\nu, t_n, \phi_n) = \exp(-i2\pi \nu t_n) \left[ \frac{\tau}{1+i2\pi \nu t_n} + \frac{A \tau}{2} \left\{ \frac{\exp(i\phi_n)}{1+i2\pi(\nu + \nu_0)} + \frac{\exp(-i\phi_n)}{1+i2\pi(\nu - \nu_0)} \right\} \right] 
\]

For convenience we may write \( F_n = \exp(-i\alpha_n) B_n \), where \( \alpha_n = 2\pi \nu t_n \) and \( B_n \) is the
term in the square brackets in eq. (9). The power spectrum $P(v)$ is then given by

$$P(v) = \left[ \sum_n F_n \right] \left[ \sum_m F_m \right] = \sum_n B_n B_n^* + \sum_m B_m B_m^* \exp\left(-i(a_n - a_m)\right)$$  \hspace{1cm} (10)

If the $t_n$'s are randomly distributed, then the last term in eq. (10) will be zero. So

$$P(v) = \sum_n B_n(v) B_n^*(v)$$  \hspace{1cm} (11)

If $f(\phi)d\phi$ is the probability that a blob starts to contribute to the intensity at a phase angle $\phi$ between $\phi$ and $\delta\phi$, we may write (11) as

$$P(v) = N \int_0^{2\pi} B(\phi,v) B^*(\phi,v)f(\phi)d\phi$$  \hspace{1cm} (12)

Here $N$ is the number of blobs or plasmoids. For a random phase distribution $f(\phi) = 1/2\pi$ and, using eq. (9) we find

$$P(v) = N \frac{2}{1+4\pi^2 - 2^2} + \frac{A^2}{4 \left(1+4\pi^2 (v-v_0)\right)^2}$$

\hspace{1cm} \frac{1}{2} - \frac{1}{1+4\pi^2 (v+v_0)^2}$$  \hspace{1cm} (13)

The first term in eq. (13) gives the LFN and is due to the fact that the intensity of each blob is always positive, as can be seen from eq. (8). The second term in eq. (13) gives a peak in the power spectrum centered around $v = v_0$. Due to the choice of the envelope function in the form of a shot, the peak has a Lorentzian profile with a FWHM of $1/\pi$. If, for example, we would have used a Gaussian this function in eq. (8) the peak would also be Gaussian and its width would be related to the width (i.e., "lifetime") of the original Gaussian envelope function. The power in the low-frequency noise is, using eq. (1), equal to $N\tau/4$ and the power in the peak is equal to $NA^2\tau/8$. Therefore, using eq. (2) the ratio of the r.m.s. intensity variation in the LFN and the QPO is given by

$$\gamma_{LFN}/\gamma_{peak} = 2^{1/2}/A$$  \hspace{1cm} (14)

Since $|A|<1$, this ratio is at least $2^{1/2}$ and we do not expect the strength of the LFN to be smaller than that in the peak.

Instead of a completely random distribution of phases $\phi_n$, we can also imagine that the blobs are again formed at random times $t_n$ but now within a narrow range of angles. Physically, this situation would arise if the magnetic field of the neutron star determines the location where the blobs or plasmoids first start to contribute to the intensity. In that case, we may put $f(\phi) = \delta(\phi - \phi_0)$. The resulting power spectra were calculated by Alpar (1985) and again
show a broad peak at $v = v_0$ and low frequency noise. The power in the LFN and in the peak are again of the same order.

Now consider the other extreme end to completely random phases and times. Suppose that each blob starts to contribute to the intensity when the former one has elapsed exactly one round through the accretion disk. In that case we may set $a_n - a_m = 2\pi (t_n - t_m) = (n-m) 2\pi v/v_0$ and $\phi_n = \phi_0 + 2\pi (n-1)$, where $\phi_0$ is the phase of the first blob. Using, eq. (9) and (10) we can write

$$P(v) = B_0 B_0^* \left[ N + 2 \sum_{p=1}^{N-1} \cos(2\pi pv/v_0) \right]$$

where $B_0 = B_n$ for each $n$, and $N$ is the total number of blobs. Since $f(\phi) = \delta(\phi - \phi_0)$ and the first term in eq. (15) gives a power spectrum with a broad peak at $v = v_0$ and LFN of roughly equal strength, for a correct choice of $A$ in eq. (9). However, the second term contributes, for sufficiently large $N$, only around $v = mv_0$ ($m = 0,1,2,3,\ldots$). The term $B_0 B_0^*$ goes to zero for $v > v_0$ (see eq. 13) and, therefore, the overall contribution of the second term in eq. (15) takes place at $v = 0$ and $v = v_0$. This has the effect that the relative power in the peak is increased with respect to the power in the low frequency noise. (See also Shibazaki and Lamb, 1987.)

4.1.2. Relation to the observations

a: Correlation between the QPO-frequency and the intensity

Assuming that in all these models the blobs, plasmoids or magnetic loops move with the Kepler velocity at $r_A$ we can obtain a relation between the beat-frequency and the observed intensity. The Kepler frequency at $r_A$ is given by $v_K = (GM/r_A^3)^{1/2}/2\pi$. Using eq. (6) and setting $v_{QPO} = n\nu_b$, the QPO-frequency is then

$$v_{QPO} = n(\lambda^{3/7} - \nu_S)$$

where $\lambda = (GM)^{1/2}4^{1/2}\mu^{1/2} /2GM)^{-3/14}/2\pi$. A quantity, often given in the literature on QPO, is the logarithmic derivative of the intensity relation (16), given by

$$\frac{d\log v_{QPO}}{d\log I} = \frac{3}{7\beta} \left[ I - \frac{1}{\nu_b(r_A)} \right]$$

where $\nu_b(r_A)$ is usually denoted by $\omega_b$, the fastness parameter (see Ghosh and Lamb, 1979).

For GX 5-1 the value for the logarithmic derivative is $\sim 2$ and for Cyg X-2 it is $\sim 1.7$. In the simple picture where $\beta = 1$ (i.e. the intensity is
proportional to the accretion rate) we see from eq. (17) that for both GX 5-1 and Cyg X-2 $v_s \neq 0$. In this case both the value for the rotation frequency of the neutron star and for the magnetic moment can be found by fitting relation (16) to the observed one. Assuming a canonical value of 10 km for the radius of the neutron star and setting $n = 1$ the derived spin periods would then be of the order of 10 ms and the surface magnetic field strengths of the order $10^9$ to $10^{10}$ G.

Therefore, if the beat-frequency model is correct the QPO-observations of both GX 5-1 and Cyg X-2 suggest that the neutron stars in these systems are rapidly rotating and have weak magnetic fields. This seems to fit in nicely with the studies of the evolution of low-mass X-ray binaries, in which the companion is an evolved stars; these systems are expected to be the progenitors of the observed wide binaries that contain a radio pulsar (see van den Heuvel (1985) for a review). Simple models for spinning up neutron stars in a binary suggest that periods of the order of 10 ms can be reached if the magnetic field strength is of the order $10^8$ to $10^{10}$ G (De Kool and Van Paradijs, 1987). This is exactly what is seen in GX 5-1 and Cyg X-2.

It must, however, be noticed that the beat-frequency model, as presented above, does not necessarily imply a rotating neutron star. If we set $v_s = 0$ in eq. (17), the logarithmic derivative becomes $\log v_{QPO}/\log I = 3/7\beta$. In the case of GX 5-1 $\beta$ would then be $\sim 0.21$ and for Cyg X-2 $\beta \sim 0.25$. Physically, this implies that in these systems the intensity does not change as fast as the accretion rate. This could, for example, happen when the system loses matter (e.g., because the accretion rate is super-Eddington) and when, if the accretion rate increases, more matter is lost. In that case the observed intensity (which is basically related to the amount of matter falling onto the surface of the neutron star) would not change as much as the accretion rate. Intermediate cases in which $\beta \neq 1$ and $v_s \neq 0$ are of course also possible, as will be shown in chapter VII, where the intensity change, due to a change in the Alfven radius (and therefore $M$), is found from the negative slope of the horizontal branch in the hardness ratio versus intensity diagram of GX 5-1. This same method could also be applied to Cyg X-2.

Although the introduction of the power $\beta$ in the relation between the observed intensity and the accretion rate has complicated matters for GX 5-1 and Cyg X-2, the situation for Sco X-1 is even worse. As was discussed in paragraph 3.2, Sco X-1 shows three different states in which the relation between the QPO-frequency and the intensity is different in each case. In the active state there is a strong positive correlation and if we can set $\beta = 1$ as was done above we can derive a value for the rotation period and for the magnetic field strength
of the neutron star. However, in the intermediate and quiescent state matters are different. In the quiescent state the left-hand side in eq. (17) is negative, which would imply that either $\beta < 0$ or $v_s > v_K(r_A)$. The latter implies that accretion does also take place when the Alfvén radius is larger than the corotation radius. This is difficult to understand in a simple picture of disc accretion. A possible solution would be that in the quiescent state of Sco X-1 we are seeing the disk and that the QPO is not due to magnetic gating (e.g., Morfill and Truemper (1986) and chapter VIII), but due to modulated disk emission. This picture does, therefore, not necessarily require accretion. Although this could possibly explain the anticorrelation between QPO-frequency and intensity in the quiescent state while still keeping $\beta = 1$, the intermediate state probably requires that $\beta \neq 1$ and that $\beta$ changes.

In general we may say that there is no obvious reason to assume that $\beta = 1$ in GX 5–1, Cyg X–2 and Sco X–1. In that case there is nothing we can say about the rotation period of the neutron star or of its magnetic field. However, if it is possible to find a relation between the black-body luminosity, originating from the surface of the neutron star, and the accretion rate, which determines the Alfvén radius, then the physical picture may become simple again, as for Sco X-1 there is a simple relation between that luminosity and the observed QPO-frequency (Van der Klis, 1986).

b: The relative strength in the QPO and LFN and the relation to intensity.

For the case treated in section 4.1.1. the r.m.s. intensity variation in the LFN and in the QPO-peak are equal to $(N\tau)^{1/2}/2I_0$ and $A(N\tau/2)^{1/2}/2I_0$, respectively, where $I_0$ is the average intensity. The strength of the low-frequency noise can, therefore, change due to a change in $N$, $\tau$ or $I_0$ while that of the QPO is also determined by the modulation depth, $A$. The latter can be found from the ratio $\gamma_{LFN}/\gamma_{QPO}$, as given in eq. (14). In GX 5-1 this ratio is approximately 1 and does not change with changing intensity, implying a modulation depth that is independent of the intensity of the source. However, in Cyg X-2 the ratio increases, which implies that $A$ decreases with increasing intensity.

The lifetime, $\tau$, of the blobs can be found from the FWHM of the QPO-peak, which is given by $1/\pi \tau$. In GX 5-1 this width increases with intensity and therefore $\tau$ decreases as the source becomes brighter. In Cyg X-2 the FWHM stays approximately constant, implying a more or less constant lifetime of the blobs or plasmoids.

We see that both sources show different relations of both $A$ and $\tau$ with intensity. This is a direct consequence of the interpretation of the observed
power spectra in terms of finite wave trains with lifetime $\tau$ and modulation depth $A$. The question why both $A$ and $\tau$ change or do not change is left unanswered, and has to be explained by the physics (see below). It seems, however, that the global behaviour of GX 5-1 and Cyg X-2 can be reasonably explained by a beat-frequency model.

The problems of the simple beat-frequency model are more complicated in the case of Sco X-1. In this source the power in the LFN is much reduced with respect to that in the QPO, which cannot be explained by a simple model in which there is a complete random phase and time distribution of blobs or plasmoids and in which the power is only determined by the lifetime of the blobs and by the modulation depth. As explained above, in order to increase the power in the QPO with respect to the power in the LFN one has to assume that all blobs start to contribute to the intensity at a specific phase and that the next blob can only start when the former has elapsed one or more rounds (i.e., the blobs have to "line up"). The requirement that the blobs start at the same phase could be explained, as pointed out above, if the magnetic field determines the location of blob formation. However, it seems very difficult to understand how each blob should know that the former one has elapsed one or more rounds. Shibazaki and Lamb (1987) suggest that fragmentation of larger-scale blobs into smaller ones or interaction between blobs may cause some spatial clustering. This mechanism is, however, not worked out in any detail. Therefore, although it is mathematically possible to increase the strength of the QPO with respect to that of the LFN, physically this seems difficult to justify.

c: Time delay

It was suggested by Hasinger (1986) that the time lag observed in Cyg X-2 for the 4.5 - 17 keV photons, with respect to the 1.0 - 4.5 keV photons is due to Compton scattering. And, of course, this mechanism may then also be responsible for the time delay observed in GX 5-1 (Van der Klis, 1986b).

Suppose the observed X-ray photons originate from the center of a spherical cloud of electrons, with a radius $R_c$. Then the average time, $t_{esc}$, for these photons to escape from the cloud will be larger than $R_c/c$, depending on the number of scatterings, and, therefore, on the optical depth, $\tau$, of the cloud. If one makes the assumption that there is no preferred direction after each scattering then the average escape time is $t_{esc} = \tau R_c/c$. However, for Compton scattering this is not exactly true. Syunyaev and Titarchuk (1980) find instead $t_{esc} = \tau R_c/2c$.

Since the average escape time mentioned above is the average escape time of all photons it cannot be set equal to the time lag observed in both Cyg x-2 and
GX 5-1. This observed time delay is, however, the difference in escape time between all photons in the high-energy band and all photons in the low-energy band.

To find the difference in escape time between photons of different energies the following problem has to be solved. Given the initial energy, $E_i$, of an incoming photon, the optical depth, $\tau$, and radius, $R_c$, of the cloud, the temperature, $T_e$, of the electron gas and given the energy, $E_f$, of the outgoing photon, then what is the escape time of the photon? This problem was solved analytically (Pozdnyakov, Sobol and Syunyaev, 1983) for the case of large optical depth ($\tau \gg 1$) and initial photon energies much less than the average energy of the electrons (i.e., $E_i \ll kT_e$). They find for two photons (1 and 2) with initial energies $E_{i1}$ and $E_{i2}$ and with final energies $E_{f1}$ and $E_{f2}$ the following time delay between photon 2 and 1

$$\Delta t = \frac{\ln(E_{f2}/E_{i2}) - \ln(E_{f1}/E_{i1})}{2\alpha + 3} \frac{mc^2 R_c}{kT_e \tau}$$

where $\alpha = -\frac{3}{2} + \left(\frac{9}{4} + \frac{\pi^2}{3}\right) - \frac{mc^2}{(\tau+2/3)^2kT_e}^{1/2}$.

However, the observed time delay is that between arrival times of photons in two rather wide energy bands, and, furthermore, the energy range from which the incoming photons originate can also be very wide. Therefore, even if the basic assumptions for which eq. (18) was derived are correct then still the expression for $\Delta t$ can only be considered as an approximation to the observed value. For cases were $\tau$ is of order unity and where the condition $E_i \ll kT_e$ does not hold, no analytic expression for $\Delta t$ can be easily found and Monte Carlo calculations have to be used.

In order to calculate the expected time delay between photons from different energy bands I have developed a computer code that treats photon scattering on electrons. This code is based on the methods developed by Pozdnyakov, Sobol and Syunyaev (1983). For an assumed energy distribution of the input photons, for $kT_e$ of the scattering electrons, and $\tau$ and $R_c$ of the cloud, this computer program generates the escape times and energy distribution of the resulting photons. From a comparison of these results with the observed differential time delay, and the X-ray spectral energy distribution a constraint may be put on the spectrum of the incoming photons, $kT_e$, $\tau$ and $R_c$.

The spectra of the bright bulge sources, such as GX 5-1 and Cyg X-2, cannot be described by simple functions, such as a black body, power law or thermal bremsstrahlung spectrum, but are composed of two or more separate components. Spectral decompositions into an "unsaturated, comptonized component" and a black
body (White et al., 1986) and into a black body and a "multi-temperature" black body (Mitsuda et al., 1985; Hirano, 1984) have been proposed.

In the two component spectra found by White et al. (1986) the blackbody component is not comptonized and therefore cannot cause a time delay. The other component is, however, due to comptonization of soft photons on hot electrons in a cloud of large optical depth. In this case the observed time delay is approximately given by eq. (18). For optical depths in the range 10 to 13, electron temperatures in range from 2 to 4 keV (consistent with values found by White et al., 1986) and for input photons selected from a black body with $kT_b \ll kT_e$, I can find reasonable fits of the calculated spectra to the observed ones for GX 5-1 and Cyg X-2. The time delay found in this case is approximately given by

$$\Delta t \sim 1.5 R_7 \text{ ms.}$$

Here $R_7$ is the radius of the cloud in units of $10^7$ cm. The observed time delay for Cyg X-2 therefore implies a radius of $\sim 2 \times 10^7$ cm, while in GX 5-1 this radius is smaller ($R_c \sim 5 \times 10^6$ cm).

In the spectra found by Hirano (1984) and Mitsuda et al. (1985) there is some evidence that the blackbody component, which is thought to originate from the surface of the neutron star, is comptonized. In that case only the high-energy tail of the observed spectrum can be used to constrain the blackbody temperature of the incoming photons, the optical depth and the electron temperature. Hirano (1984) finds for Cyg X-2 an optical depth of 4, an electron temperature of $kT_e = 7$ keV and a blackbody temperature of $kT_b = 1.2$ keV. In that case, my calculations show an expected time delay of

$$\Delta t \sim 0.1 R_7 \text{ ms.}$$

I have also performed calculations to obtain reasonable spectral fits to the high-energy tail of the spectrum of GX5-1, using blackbody temperatures larger than 1 keV. For an optical depths in the range 2 to 4, electron temperatures between 5 and 8 keV and black-body temperatures in the range 1.2 to 1.4 keV, I am able to find reasonable fits. The time delay is then approximately given by

$$\Delta t \sim (0.1 - 0.3) R_7 \text{ ms.}$$

These values for the expected time delay between photons in different energy bands are about an order of magnitude smaller than the values found from fitting the unsaturated, comptonized spectra (see above), which implies a much larger
radius in the former case than in the latter. Therefore, once the origin of the observed spectra is know in more detail the time delay in the QPO can be used as a measure for the dimension of the electron cloud.

It is important to note that there is a considerable difference in observed time delay and therefore $R_c$ between GX 5-1 and Cyg X-2. This is surprising since the behaviour of the sources is very similar, and identifying $R_c$ with the Kepler radius associated with the QPO-frequency, as suggested by Hasinger (1986), is very uncertain.

4.1.3. Other questions

Except for the problems already discussed above, there are more questions that must be asked in all magnetospheric models. A basic problems in these models is that if the magnetic field of the neutron star is able to create a magnetosphere one would expect that it is able to control the accretion flow inward onto the surface; if a more or less dipole structure of the field is assumed, it then seems likely that matter falls onto a polar cap. In general, one does not expect that in all sources the magnetic and rotation axes are aligned, so that due to the rotation of the neutron star one would expect the X-ray intensity to be modulated with the rotation frequency of the star. However, the observations of the best studied sources (Sco X-1, Cyg X-2 and GX 5-1) do not show such a modulation.

There may be several ways to reduce the expected modulation, as pointed out by Lamb et al. (1985). First of all, due to the relatively weak strength of the magnetic field, the polar cap may be quite large, thereby reducing the modulation. Furthermore, there is evidence for a cloud of scattering material surrounding some low-mass X-ray binaries; in some cases the observed spectra show evidence for comptonization (White et al., 1986); for Cyg X-2 and GX 5-1 the observed time delay can be interpreted as the result of scattering of photons (sections 3.5 and 4.1.1c); from the light curves of some sources there are also indications for the presence of coronae (White and Mason, 1984).

If the neutron star emits a directed beam of radiation then each photon in the beam is scattered in the cloud, thereby changing its direction. Depending on the number of scatterings (i.e., on the optical depth of the cloud) the modulation of the intensity, as seen by a stationary observer outside the cloud, is reduced. The radiation of the QPO, however, is not directed and the modulation would even be seen by someone fixed in the rotating frame of the star. The only effect the cloud has on the modulation of the QPO is time-smearing due to the scattering. This effect becomes important when $\tau_c R_c/c > 1/\nu_{\text{QPO}}$. Therefore, for observed frequencies of around 30 Hz this effect is not
important for typical cloud dimensions of $r_c \sim 10^7$ cm as long as $\tau_c$ (i.e., the Compton optical depth) is less than 100.

In order to simulate the effect of scattering on the expected modulation of a rotating beam, I performed some Monte Carlo calculations. A rotating beam with a half width of $25^\circ$ (i.e. approximately the expected half width of the polar cap for $r_A \sim 6$ R), consisting of monoenergetic photons of energy $E_{\text{ph}} = 5$ keV, was put at the center of a cloud of optical depth $\tau_c$ and temperature $kT_e = 5$ keV. In Fig. 1, I plotted the expected relative modulation $m = \text{mod}(\tau=\tau_c)/\text{mod}(\tau=0)$ as a function of optical depth $\tau_c$. It is noted that at $\tau_c = 10$ the modulation is still of order 5%. Since EXOSAT is able to detect a modulation in the intensity down to a level of about 0.3% (van der Klis et al., 1985) these calculations show that in order to reduce the modulation below this threshold the cloud has to have an optical depth much larger than 10.

![Figure 1: The expected relative modulation as a function of the optical depth for a rotating beam with an initial width of $50^\circ$. The initial energy of the photons is 5 keV and the temperature of the electron gas is 5 keV.](image)

In the model of Morfill and Truemper (1986) it is indeed assumed that the optical depth is of order $10^3$. As shown above, this large value would also reduce the modulation in the QPO. Therefore, in their model the QPO is not due to modulated accretion, originating from the surface of the neutron star, but from the inner edge of the accretion disk, situated at more than 10 stellar radii. There are indications from fits of the spectra of, e.g., GX 5-1 and Cyg
X-2 (cf. Hasinger et al., 1986; Mitsuda et al., 1985) that the black-body component, thought to originate from the surface, is comptonized. However, the typical values for the optical depth, needed to fit these spectra are less than 10 and in that case the absence of modulation at the rotation frequency of the star is difficult to understand. And it is indeed this problem that has stimulated research into other, non-magnetospheric models for QPO (see below).

Other questions regarding magnetospheric models are related to the physical mechanisms in these models. For example, it is clear from the observations of GX 5-1 that the modulation depth, $A$, is of order one. Furthermore, the large power in the QPO relative to that in the zero-frequency bin (i.e., $Y_{QPO}$ in GX 5-1 can be as large as 6%, while in other sources, such as the Rapid Burster it is even larger; Stella et al., 1985), implies that the absolute contribution of each blob to the intensity is large. In the magnetic gating models of Lamb et al. (1985) and in the model presented in chapter VI this implies that the interaction between matter in the disk and the field must be very efficient. In the case that the QPO are due to modulated accretion from blobs this implies that the field must be able to penetrate a large portion of the blob within one beat-period, $P_b = 1/\nu_b$. The time $\tau_D$ for the field to diffuse into the blob is approximately equal to

$$\tau_D = 4\pi \sigma L^2/c^2$$  \hspace{1cm} (19)

Here, $\sigma$ is the conductivity of the plasma and $L$ is the typical size of each blob. For a fully ionized plasma the conductivity is given by

$$\sigma = \frac{3m_e}{16\pi^{1/2}Z^2e^2mNe} \left(\frac{2kT_e}{m_e}\right)^{3/2}$$  \hspace{1cm} (20)

where $m_e$ is mass and $e$ the charge of the electron, $T_e$ the temperature of the electrons, $Ze$ the charge of the ions and $\Lambda = 3kT_e^{3/2}2^{1/2}\pi^{1/2}m_n^{1/2}e^3$ (cf. Kral and Trivelpiece, 1973). For fully ionized hydrogen, assuming $n_e \sim 5 \times 10^{19}$ cm$^{-3}$ and $T_e \sim 10^7$ K (where I have used the values for the inner region of a standard accretion disk at $r_A = 6 \times 10^6$ cm; cf. Shapiro and Teukolsky, 1983) we find $\sigma \sim 2 \times 10^{17}$ s$^{-1}$. If we assume the blobs to have a characteristic size of the order of the thickness of the disk (i.e., $L \sim 10^6$ cm) then the diffusion time of the field is given by $\tau_D \sim 1000$ yr. Therefore, the field is unable to penetrate the blob on a timescale as short as the beat-period. This is mainly due to the high value of the conductivity. In order to reduce the latter anomalous processes have to be invoked, such as small scale turbulence in the blob. However, this would probably destroy the blob itself and thereby the QPO.

A possible mechanism would be that the blobs move through a medium of
matter that is already attached to the field lines and corotating with the star. Due to this relative motion, a magnetic Kelvin-Helmholtz instability is initiated at the surface of the blob. The growth rate depends on the ratio of the densities of the blobs and magnetospheric matter, and on their relative velocity, which in this case is the difference between the Kepler velocity and corotation velocity at the Alfvén radius. The KH-instability strips the outer layers from the blob, resulting in sprays of matter that are small enough for the field to diffuse into on a short timescale. For a similar calculation in the case of spherical accretion Arons and Lea (1980) showed that the timescale of the instability can be can short (i.e., shorter than the freefall timescale) but that the penetration depth is not very large. This would in our case cause a problem, as the modulation depth must be large.

In order to avoid the problem of field penetration into blobs, in chapter VI it will be argued that regions of turbulence are formed in the disk, for which the conductivity is much reduced, thereby increasing the interaction with the field.

From the above it follows that the precise interaction between the blobs, or regions of reduced conductivity, and the magnetic field is an important problem in magnetic-gating models of QPO, which has to be solved in order to understand the observed lifetimes of the blobs and their relation with intensity. Also, the relation between the modulation depth and the intensity cannot be understood unless this problem is solved.

In the model of Morfill and Truemper (1986) the plasmoids moving in the disk at $r_A$ do not interact with the magnetic field (i.e., their model is not a magnetic gating model) but with shocks that move through the disk with the corotation velocity. The modulated intensity as seen in the QPO is therefore not due to accretion but to modulated heating of the plasmoids by the passing shocks. The central problem in such a model becomes then the explanation of the power in the QPO peak, since there may not be enough energy available in the disk.

If the accretion disk processes a rate $\dot{M}_d$ then the emitted, total luminosity from the disk is approximately equal to $L_d = GM_d^2/2r_A$, where $M$ is the mass of the neutron star. The luminosity coming from the surface of the star is equal to $L_s = GM_s^2/R_s$, where $\dot{M}_s$ is the rate of accretion onto the neutron star. Usually it is assumed that all matter in the disk eventually reaches the star and therefore $\dot{M}_d + \dot{M}_s$. Since for neutron stars, with magnetic field strengths of the order of $10^7$ to $10^{10}$ G, $r_A > 5 R$ we do not expect the total luminosity of the disk to be more than $\sim 10\%$ of the total luminosity of the system. In that case it is difficult to see how the QPO can comprise of order $10\%$ of the total
intensity, assuming they originate in the disk, since that would imply a 100% modulation of the intensity of the disk. Morfill and Truemper, therefore, argue that $\dot{M}_d \gg \dot{M}$. The accretion rate onto the star is approximately equal to the Eddington accretion rate, while the disk is able to process a much higher rate. This implies that part of the matter is blown away from the system, thereby contributing to the high optical depth needed to reduce the expected modulation at the rotation frequency of the star (see discussion above). Therefore, in this case we are mainly seeing the disk and the strength of the QPO could now be explained by a 10% modulation of the disk luminosity. Morfill and Truemper then argue that if the intensity increases more matter is blown away, thereby increasing the optical depth and reducing the modulation depth, $A$, which leads to a decrease of the power in the QPO. The latter could, indeed, explain, the behaviour of Cyg X-2, where the modulation depth has to decrease with increasing intensity, as discussed above. However, in the case of GX 5-1 the modulation depth is of order unity and does not change. Here, it is probably the lifetime, $\tau$, that has to change instead of $A$. Although an increase in the optical depth may change $A$ in one source it is difficult to understand why it should change $\tau$ and leave $A$ constant in another.

4.1.4. Refinements

As discussed above, all the magnetospheric models proposed so far have problems explaining various aspects of the behaviour of the observed QPO-sources. Most models, however, contain one or more parameters that may change from source to source or even within one source, such that the different observed properties can be taken into account. I have not mentioned all these parameters as most seem quite ad hoc and are not based on detailed physics. One parameter that was mentioned was the power $\beta$ in eq. (5), which relates the observed intensity to the accretion rate. Here, I will give one more example.

Until now we have argued that the power in the LFN and in the QPO is only a function of the lifetime and of the modulation depth. However, in the model of Lamb et al. (1985) it is argued that the blobs do not rotate exactly at $r_A$ but in a finite region $\Delta r = \delta$. Therefore, there is also a spread in the Kepler frequency and therefore also in the QPO-frequency, which contributes to the width of the peak and its power. In this way, the changes observed in the power of the LFN and the QPO with changing intensity may then be explained by changes in $\tau$, $A$, $N$ and/or $\delta$.

As long as the physics is not worked out in more detail one may introduce more and more parameters to explain all the different observations. Although, in this way it becomes impossible to falsify the beat-frequency model, it also
destroys the beauty, inherent in the simple theory put forward by Alpar and Shaham (1985).

4.2. Non-magnetospheric models

4.2.1. The disk-corona model of Boyle, Fabian and Guilbert

Boyle et al. (1986) suggest that the accretion disk, surrounding the central X-ray source, contains a corona and that a fraction of the X-rays, emitted by the source, is scattered by this corona. The compact object is not necessarily a neutron star but may also be a black hole and it has no magnetic field that is able to channel the gas flow onto the star. Therefore, in this model no modulation is expected at the rotation frequency of the central object. The authors suggest that individual sites in the disk-corona system, situated at a distance $r_s$ from the X-ray source, oscillate with the local Kepler frequency. If one assumes that these oscillations modulate the amount of radiation scattered into the direction of the observer, then QPO are expected, with frequency $v_{QPO} = v_K(r_s)$.

The scattering of radiation occurs approximately at the $\tau = 1$ surface in the corona, where $\tau$ is the optical depth from $r_s$ to the X-ray source. Boyle et al. find

$$\tau = (aL_{\nu}/\beta^2) \exp(-\beta^2/r)$$

where $a$ is $10^{-3}$ times the constant fraction of the incident flux that gets scattered down onto the disk, $\beta$ is the angle between the incident radiation and the plane of the disk (i.e., $\beta = z/r$, where $z$ is the height of the top of the corona at $r$), $L$ is the luminosity of the compact object, $\sigma_T$ is the Thomson cross-section for electron scattering and $\beta = GM_{\text{BH}}/4kT_C$, where $T_C$ is the coronal temperature.

From eq. (21) a relation can be found between the Kepler frequency at $r_s$ (and therefore the QPO-frequency) and the observed intensity $I$, of the form

$$v = v_0 (\log I - C_0)^{3/2}$$

where $v_0$ is a constant and $C_0$ still depends on the ratio between $I$ and $L$. Fits of relation (22) to the observed QPO behaviour of GX 5-1 yield $\theta \sim 2^\circ$ and $r_s \sim 2.3 \times 10^7$ cm (assuming $T_C = 5 \times 10^7$ K).

Since the observed QPO-peaks in the power spectrum have a typical relative width $\Delta v/v$ of 10 to 20%, the spread in $r_s$ must be small (i.e., $|\Delta r_s/r_s| = 2\Delta v/3v \sim 5$ to 15%), implying that the $\tau = 1$ surface must be very steep at $r_s$. To see
whether this is indeed the case we set $\tau = 1$ in eq. (21) and convert $\theta$ to $z$. We then find

$$\frac{dz}{dr} = \left(\frac{2}{r} + 3\beta z/r^4\right)/(2/z + \beta/r^3)$$

(23)

Using $r_\text{s} = 2.3 \times 10^7 \text{ cm}$, $z = r_\text{s}\tan\theta = 8 \times 10^5 \text{ cm}$, $T_\text{c} = 5 \times 10^7 \text{ K}$ and $M = 1.4 \, M_\odot$ we find $dz/dr = 0.03$, implying an angle $\phi = 2^\circ$ for the $\tau = 1$ surface, which is not at all steep! Therefore, the coronal oscillations must be very localized to reduce the spread in $r_\text{s}$ and thereby in $\nu_{\text{QPO}}$. This seems difficult to justify. The authors, therefore, suggest that the steepness, $dz/dr$, of the $\tau = 1$ surface can be increased by non-linear effects. However, as these effects are not worked out in any detail, they may work in either way, and do, at this moment, not solve the problem.

Another problem in this model may be the explanation of the power observed in the quasi-period oscillations. This can only be understood if the corona is able to scatter an appreciable amount of radiation and the modulation is very efficient. However, at the small angles inferred from the model (i.e., $\theta = 2^\circ$) the amount of scattered radiation is probably small. Again, this angle and thereby the amount of scattering may be increased by non-linear effects, but models for these effects need to be developed, before anything definite can be said.

4.2.2. The "neutron-star spot" model of Hameury, King and Lasota

Hameury et al. (1985) argue that the QPO seen in some low-mass X-ray binaries are due to bright spots in the boundary layer of the neutron star. These spots are formed in regions where the heat conduction is increased by the presence of magnetic fields, created by dynamo action in the turbulent boundary layer between the disk and the surface of the neutron star. These spots rotate and appear and disappear behind the edge of the star as seen by a distant observer. Because of their finite lifetime, due to shearing in the layer, these spots cause QPO and LFN.

Since the spots in the turbulent layer may have any frequency between the rotation frequency of the star and the Kepler frequency at the top of the layer (i.e., edge of the disk), it is not clear in this model why the observed width of the QPO-peak is so small. Nor is it clear how this frequency is related to the intensity. These problems, I think, are so fundamental that they have to be solved first (as they have been more or less in, e.g., the beat-frequency model) before this model can be seriously considered as a QPO-model. Furthermore, as the physics of the turbulent layer is poorly understood, other questions, like the lifetime of the spots and such must be answered. However, the problem of
detailed physics is a common feature in all QPO-models.

4.2.3. The occultation model of Van der Klis et al.

In order to explain the absence of LFN and modulation at the rotation frequency of the neutron star, which are real problems in the beat-frequency model, Van der Klis et al. (1986) suggested that the QPO are due to occultation of the central source by an oscillating, thick disk. In this way the power in the LFN noise can be much reduced as was shown by Van der Klis et al. However, a problem may be that in order to see QPO, due to the oscillation of the rim of the disk, the observer has to view the source within a very narrow range of inclination angles. In this way it becomes difficult to understand why so many QPO sources are seen in this class of objects (i.e., LMXB). Nor is it easy to understand how the observed frequency is related to the intensity of the source.

5. Conclusion

Our knowledge of such basic properties as the magnetic field strength or rotation period of neutron stars in bright galactic bulge sources is very poor. Therefore, the discovery of quasi-periodic oscillations in some of these sources can be of great importance to our understanding of the neutron stars in these systems and their evolution. However, until now no theory has been developed that can explain all the different features in the observations satisfactorily.

The models that have been worked out in most detail are the magnetospheric or beat-frequency models. Although these models have some serious difficulties, they seem to fit in nicely with the idea that some of the bright galactic bulge sources may be the progenitors of the binary radio pulsars. This I believe is a very strong argument in favour of these models. Therefore, serious attention should be devoted to a further development of magnetospheric models for QPO.

The non-magnetospheric models that have been developed so far to explain QPO also have serious difficulties. However, they have not been worked out in such detail that they can be easily refuted.

My conclusion is that at this moment our understanding of QPO is still very limited, but that this situation may improve as the models that have been presented so far are worked out in more detail.

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