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CHAPTER VII

BIMODAL ACCRETION IN GX5-1 AND A POSSIBLE CONSTRAINT ON ITS ROTATION PERIOD

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Summary

In this paper it is argued that the low mass X-ray binary GX5-1 exhibits two modes of accretion, due to a difference in the accretion rate from the companion. For high accretion rates accretion occurs uniformly over the stellar surface. When GX5-1 is seen on the normal branch in the intensity vs hardness ratio diagram it is in this mode. For a somewhat lower accretion rate the magnetic field of the star prevents the disc from reaching the star and the disc stops at a magnetospheric radius which depends on the accretion rate. In this mode accretion will take place over a small polar cap. Due to the interaction of the disc with the field quasi-periodic oscillations will be present in this mode and the source is on the QPO branch in the intensity vs hardness ratio diagram. The specific behaviour of this branch leads to a relation between the magnetospheric radius, \( r_A \), and the photon count rate from the source, of the form \( r_A \propto N^{-\lambda} \), \( \lambda > 1 \). It is also shown that in terms of this model the rotation period of the neutron star is longer than 0.1 s.

1. Introduction

It is generally thought that the low-mass X-ray binaries consist of a neutron star and a low-mass companion. Roche-lobe overflow drives mass transfer from the companion onto the neutron star via an accretion disc. Most of these sources do not show X-ray pulsations, which seems to imply that the magnetic field of the neutron star is too weak to channel the accretion flow and the disc is therefore thought to extend down to the surface of the star (see for review: Lewin and Joss, 1983).

Interpretations of recent observations made with the ME detector on EXOSAT (van der Klis et al., 1985(1); Hasinger et al., 1985; Middleditch and Priedhorsky, 1985) now suggest that some of the neutron stars in the low-mass X-
ray binaries (e.g., GX5-1, Sco X-1, Cyg X-2, MXB1730-335) have fields in the order of $10^8 - 10^{10}$ Gauss. Power spectra derived from these observations typically show a red noise component and a broad peak at a few tens of Hertz, which is thought of as being due to quasi-periodic oscillations (QPO's).

In GX5-1 the centroid frequency and the width of the peak as well as the slope of the red noise change, and are well correlated with the X-ray intensity (i.e., count rate) of the source (van der Klis et al. 1985(1)). Alpar and Shaham (1985) have suggested that the observed frequency of the peak in the power spectra is due to a beat between the Kepler frequency at the inner edge of the accretion disc (taken to be the magnetospheric or Alfvén radius, $r_A$) and the rotation frequency of the neutron star. From this they derive a relation between the intensity of the source and the beat frequency, that fits well to the data of GX5-1. In some of the QPO sources the beat frequency model seems unable to account for the frequency vs intensity behaviour. This model is not the only method of producing oscillations of the observed frequency and other models have been proposed (Boyle et al., 1985; Hamer et al., 1985). In this paper the implications of bi-model accretion are discussed for the beat frequency model only. This model assumes that in order to produce such a beat frequency, an asymmetry in the stellar magnetic field must interact with structures in the inner region of the disc. Lamb et al. (1985), Berman and Stollman (1986) and van der Klis et al. (1985(1)) have suggested that the magnetic field acts as a gating mechanism for the accretion flow from these structures.

GX5-1 was also observed with the GSPC on EXOSAT and a intensity vs hardness ratio diagram was produced (van der Klis et al., 1985(II)). The most important feature of this diagram is the fact that it consists of two curves or branches. On what will be referred to in this paper as the normal branch the hardness ratio (i.e., the ratio of photon counts in the 6 to 10 keV band to photon counts in the 3 to 6 keV band) increases monotonically from ~ 0.4 to ~ 0.55 as the count rate (i.e., the total number of photons detected by the GSPC per second in the 3 to 10 keV band) increases from ~ 90 cps to ~ 180 cps. When the source is on this normal branch no QPO's are observed.

The second branch has a quite different behaviour. As the count rate increases from ~ 90 cps to ~ 180 cps the hardness ratio decreases from ~ 0.65 to ~ 0.60 monotonically. When the source is on this branch QPO's are observed. Throughout this paper therefore, this branch is called the QPO branch.

This two branched structure has previously been observed with HAKUCHO (cf. Mitsuda, 1984). In those observations it was noted that for about 90% of the total observation time the source showed time variations similar to those of Sco X-1 (White et al., 1976) on time scales of hours. During the rest of the
observation time the source was on the "horizontal" (QPO) branch, where it stayed for about 5 days. It was also noted that GX5-1 moved in the intensity vs hardness ratio diagram almost exactly on one branch or the other at a given time. According to Mitsuda this leads to the conclusion that it must switch from one branch to the other at the brightest point.

GX5-1 was also observed by TENMA (Mitsuda, 1984). During these observations the source was on the normal branch and it was shown that the spectra were composed of two components. Several of the low mass X-ray binaries that were observed in detail with TENMA (Mitsuda, 1984) and more recently with EXOSAT (White et al., 1985) show these two component spectra. One component can be fitted to a black-body spectrum, and is therefore thought to originate from the stellar surface, while the second component is fitted either to a multi-colour black-body spectrum or to an unsaturated Comptonised spectrum where low energy photons are scattered by high energy electrons, and is identified as coming from the disc.

As stated above GX5-1 was not observed on the QPO branch with TENMA and therefore no detailed spectra were available. It was thought however that this branch could be explained by a simple extrapolation of the two component model (Mitsuda, 1984). Mitsuda argues that if the highest intensity observed can be identified with the Eddington luminosity and if the source switches branches at this point, then the QPO branch might represent super-Eddington accretion, changing the intensity vs hardness ratio behaviour.

In this paper it will also be argued that the existence of the two branches is due to a difference in accretion rates, however on the QPO branch the accretion rate is somewhat lower than on the normal branch and mode changing does not necessarily occur at the point of highest intensity on both branches. It will be shown how this fits in with the beat frequency model and leads to constraints on both the relation between the Alfven radius and the intensity and on the stellar rotation period.

2. The Model

It is proposed that the two branched structure of the intensity vs hardness ratio diagram is a result of two distinctly different modes of accretion onto the neutron star. On the normal branch there is a high accretion rate, and accretion occurs more or less uniformly over the whole surface of the star and is largely unaffected by the stellar magnetic field, and consequently no beat frequency is observed. On the QPO branch the accretion rate is somewhat lower, and at some radius the stellar magnetic field is able to direct the accretion flow, thus defining an Alfven radius $r_A$. This is the only definition of $r_A$ for
In this paper, there is no a priori assumption as to the dependence of $r_A$ on the accretion rate $\dot{M}$. In this case the usual mechanism, described above, produces the beat frequency, and accretion takes place along the field lines onto a small polar cap, as in the normal X-ray pulsars (Rappaport and Joss, 1983).

The hardness ratio is assumed to be locally monotonically related to the emitted flux per unit area; as, for example, is the case with a black body. On the normal branch the emitting area is constant, and an increase in flux must be associated with an increase in the hardness ratio. On the QPO branch however the emitting area may change and if it is increased fast enough whilst the flux emitted per unit area is reduced there may be an increase in the overall flux received for a reduced hardness ratio, thus producing a negative slope in the intensity vs hardness ratio diagram. It is shown that this together with the observed behaviour of the beat frequency with count rate of the source leads to a constraint on the Alfven radius.

The hardness ratio $H(T)$ of the source as given by van der Klis et al. (1985(II)) is defined from the ratio of the photon counts in the 3 to 6 keV band to the photon counts in the 6 to 10 keV band and from this a colour temperature $T$ may be defined by the relation

$$H(T) = \frac{\int_{3/kT}^{0} \exp(x) - 1 \, dx}{\int_{6/kT}^{\infty} \frac{x^2}{\exp(x) - 1} \, dx}$$

where $k$ is the Boltzmann constant expressed in keV per degree. Thus for a blackbody the colour temperature would be equal to the thermodynamic temperature. It is assumed that at a colour temperature $T$, unit area of the stellar surface emits energy $E_0 = E_0(T)$. The total luminosity of the star $L$ is then given by $\int E_0(T) \, ds$ where the integral is taken over the stellar surface.

If every element of area is an isotropic emitter, with intensity $I_0$ normal to the surface, then,

$$E_0 = \int_{0}^{2\pi} \int_{0}^{\pi/2} I_0(T) \cos \theta \sin \theta \, d\theta \, d\phi = \pi I_0(T)$$

If the star accretes uniformly over a polar cap extending from colatitude $\theta = 0$ to $\theta = \theta_0$, and not outside that cap, then the flux received at a distance $d$, by an observer directly above the cap is,

$$F(d, \theta_0) = \frac{R_*^2}{d^2} \int_{0}^{\theta_0} \int_{0}^{2\pi} I_0(T) \cos \theta \sin \theta \, d\theta \, d\phi$$

where $R_*$ is the stellar radius. Thus where $T$ is a constant over the stellar surface,
\[ F(d, \theta_0) = E_0(T) \frac{R^2}{d^2} \sin^2 \theta_0 \]  

(4)

and the total luminosity of the star is,

\[ L = \frac{4\pi F(d, \theta_0) d^2}{(1 + \cos \theta_0)} \]

(5)

It is also assumed that the average energy \( E_p \) of the photons in the radiation field relates simply to the temperature, by a relation of the form,

\[ E_p(T) = bT^\zeta \]

(6)

and so the flux may be written in terms of the photon flux \( N \) as,

\[ F(d, \theta_0) = NE_p(T) = NbT^\zeta \]

(7)

where \( N \) is the total number of photons received per unit area per second. With eq. (4) this gives the relation,

\[ NbT^\zeta = E_0(T) \frac{R^2}{d^2} \sin^2 \theta_0 + F_d \]

(8)

where \( F_d \) is the flux received from the disc, which is shown in the next section to be small in comparison with the flux from the star and has been ignored in the following discussion. If accretion occurs from some radius \( r_A \), defined by the magnetic field interaction with the disc, and matter accretes along field lines onto the star, then from the geometry of the assumed dipole field,

\[ R^* = r_A \sin^2 \theta_0 \]

(9)

and so eq. (8) becomes,

\[ E_0(T) T^{-\zeta} = \frac{bd^2 N r_A}{R_A^3} \]

(10)

It may be noted that equation (10) simply relates the number of photons produced at the stellar surface to the number received per unit area. Therefore,

\[ \frac{E_0(T)}{T^{\zeta+1}} \left( \frac{d \log E_0(T)}{d \log T} - \zeta \right) \frac{dT}{dN} = \frac{bd^2}{R_A^3} \left( r_A + N \frac{dr}{dN} \right) \]

(11)

The negative slope of the upper branch of the curve in the intensity vs hardness ratio diagram requires that \( \frac{dT}{dN} < 0 \) if the coefficient of \( \frac{dT}{dN} \) is positive, thus
\[
\frac{d \log r_A}{d \log N} < -1
\]  \hspace{1cm} (12)

If \(v_K\) is the Kepler frequency at the radius \(r_A\) then,
\[
\log r_A = \frac{1}{3} \log \left( \frac{GM}{4\pi^2} \right) - \frac{2}{3} \log v_K
\]  \hspace{1cm} (13)

and so,
\[
\frac{d \log r_A}{d \log N} = -\frac{2}{3} \frac{d \log v_K}{d \log N}.
\]  \hspace{1cm} (14)

Then eq. (12) implies,
\[
\frac{2}{3} \frac{d \log v_K}{d \log N} > 1
\]  \hspace{1cm} (15)

As \(v_K = v_b + v_*\) where \(v_b\) is the observed beat frequency and \(v_*\) is the stellar rotation frequency, eq. (15) becomes
\[
\frac{d \log v_b}{d \log N} > \frac{3}{2} \frac{v_k}{v_b} = \frac{3}{2} \frac{1}{1 - \omega_s}
\]  \hspace{1cm} (16)

where \(\omega_s\) is \(v_*/v_k\), the fastness parameter (Ghosh and Lamb, 1979). The results derived above depend on the spectrum of the source, defined by \(E_0(T)\) and \(E_\sigma(T)\), only through the condition in equation (11) that the coefficient of \(\frac{dt}{dN}\) be positive. The manner in which this constrains the possible spectra is now investigated.

In general \(E_0(T)\) may be written as a power series in \(T\) in the form
\[
E_0(T) = (T - T_0)^s \sum_{i=0}^{\infty} a_i (T - T_0)^i; \quad 0 < s < 1
\]  \hspace{1cm} (17)

where \(T_0\) is an arbitrary temperature typically in the region of negative slope. In which case the condition for the coefficient of \(\frac{dt}{dN}\) in eq. (11) to be positive reduces to,
\[
(T - T_0)^{p + s - 1} \sum_{i=0}^{\infty} \left( a_{i+p}(i + p + s) - \frac{a_{i+p-1}
\right) (T - T_0)^i > 0
\]  \hspace{1cm} (18)

where by definition \(a_{p-1} = 0\) and in the limit as \(T \rightarrow T_0\) this reduces to the condition
\[
(T - T_0)^{p + s - 1} \left( a_{\alpha p}(\alpha + p + s) - \frac{a_{\alpha p-1}}{T_0} \right) > 0
\]  \hspace{1cm} (19)

where \((s = 0, \alpha = 1)\) and \((s \neq 0, \alpha = 0)\).

Then this gives,
\[
(\alpha + p + s) a_{\alpha p} > \frac{a_{\alpha p-1}}{T_0},
\]  \hspace{1cm} (20)
valid $\forall T > T_0$ and $\forall (p+s-1)$ even. Here $p$ is the index of the first non-zero coefficient in the series. Clearly the requirement that $E_Q(T)$ is reasonably physically in the region $T = T_0$ will place additional constraints on $E_0(T)$, however, it may be seen that the results derived up to equation (16) will be true for a very large class of source spectra, which is a necessary condition, as at present the processes present in these sources determining $E_0(T)$ and $E_p(T)$ are not understood. In the case of a black body $s = 0$, $\zeta = 1$, $b = 2.7k$, $a_0 = \sigma T_0^4$, $a_1 = 4\sigma T_0^3$, $a_2 = 6\sigma T_0^2$, $a_3 = 4\sigma T_0$, $a_4 = \sigma$, where $\sigma$ is the Stephan-Boltzmann constant, and it may be seen that eq. (18) is satisfied.

3. Discussion

One of the observables for the QPO's in GX5-1 is the logarithmic derivative of the beat frequency with count rate. The count rate per unit area $N'$ for the detectors (ME, GSPC) on EXOSAT is not equal to the $N$ in the equations above, because of the limited bandwidth of the detectors. The relation between the two is given by,

$$N = fN'$$

(21)

where $f$ is in fact weakly temperature dependent, but over the small variation in temperature for the QPO branch is taken to be a constant. Then (16) may be written as,

$$\frac{d \log v_b}{d \log N'} \geq \frac{3}{2} \frac{1}{1 - \omega_s}$$

(22)

The observed value for this derivative varies slightly with $N'$ but is of order 2 (van der Klis et al., 1985(1)). Taking this value gives

$$\omega_s \leq \frac{1}{4}$$

(23)

From this the maximum rotation frequency of the star can be derived as $v_{\star} < v_b/3$, and the maximum Kepler frequency at the Alfven radius as $v_K < 4v_b/3$. For an observed beat frequency of the order of 30 Hz this gives $v_{\star} < 10$ Hz (period $> 0.1$ s), and an Alfven radius of the order of 140 km. This value of $r_A$ may be inserted into equation (10) along with the distance $d$ to the source of 8.4 kpc (derived below). If $E_0(T)$ and $E_p(T)$ are known a colour temperature $T$ for the source can then be derived, and this should be consistent with the observed value, given from the hardness ratio. It is not expected that the emitted spectrum will be a black-body spectrum. Berman and Stollman (1986) argue that emission from accretion onto polar caps will be comptonized by the cold accretion column. Such a process would scatter the photons to lower energies,
thus softening the spectrum, whilst conserving the number of photons. Such accreting matter would, for objects with high accretion rates, be optically thick and so care should be taken in defining the apparent stellar radius $R_*$ in equation (10), which should then be at the $\tau = 1$ surface of the accretion column, and may well be as much as 1.5 times the actual stellar radius. If a black body spectrum were to be assumed, then with the given values of $r_A$ and $d$ equation (10) suggests that $T \sim 3 - 10$ keV on the QPO branch, and that would strongly disagree with the observed hardness ratio of 0.6 - 0.65, which for a black-body implies a temperature $T \sim 1.8 - 1.9$ keV. Thus this supports the expectation of a non-black-body spectrum.

These values for the period and Alfvén radius are larger than those previously obtained from the beat frequency model (Alpar and Shaham, 1985; van der Klis et al., 1985(I)). As a consequence of the large Alfvén radius the maximum flux from the disc is less than 4% of the total, which justifies ignoring $F_d$ in eq. (8). In previous work $v_b$ has been derived by fitting the data for $v_b$ and $N'$ to the specific form $v_b = AN'^{3/7} - v_*$, derived from the relation for the Alfvén radius in terms of $N'$,

$$r_A = N'^{-2/7}.$$  (24)

This relation may be derived using either assumptions applicable only to spherical accretion, or crude assumptions as to the interaction of the disc with the stellar magnetic field. In either case this relation is only true providing that $N' = \dot{M}$, the accretion rate. Even if $\dot{M} = L$, which is the case if all the accretion energy is converted into radiation, then equations (3), (5), (7) and (21) show that $L$ is not simply proportional to $N'$. This to some extent accounts for the need of Lamb et al. (1985) to introduce an arbitrary factor $\beta$ to obtain fits to the data of some of the sources. In the model above eq. (12) requires that $r_A = N'^{-\lambda}$, $\lambda > 1$, which is quite different from relation (24).

In principle at least, if the functions $E_0(T)$ and $E_p(T)$ are known for the source, then (11) leads to a solution for the stellar frequency in terms of $\frac{dT}{dN}$ and $\frac{dv_b}{dN}$. The first of these can be obtained via the intensity vs hardness ratio diagram and the second from the various power spectra (van der Klis et al., 1985(I)). Necessarily simultaneous observations of the hardness ratio and the beat frequency are required to obtain these two quantities for a particular state of the source. If $v_*$ is found from eq. (11), then also $r_A$ may be plotted against $N$ to give the true variation of $r_A$ with $N$.

If the normal branch is due to accretion over the whole surface of the star and the spectrum is approximated by a single temperature black body, then the
distance $d$ may be estimated from (8), which becomes,

$$\frac{d^2}{R_*^2} = \frac{\sigma T^3}{2.7 kN},$$

where $f^{-1} = \frac{1}{2.404} \int_{E_1/kT}^{E_2/kT} \frac{x^2}{\exp(x) - 1} \, dx \quad (25)$

$E_1 \to E_2$ is the pass band of the detector. This relation can be fitted to the normal branch in the intensity vs hardness ratio diagram using eq. (1), and for a value of $R_*$ of $10^6$ cm gives a value of $d$ of $\sim 8.4$ kpc, which is in agreement with the general assumption that the bright galactic bulge sources are concentrated around the center of our galaxy (Lewin and Joss, 1983).

It has been argued (Lewin and van Paradijs, 1985) that the interpretation of the observed spectra of GX5-1 in terms of two component models may contradict the beat-frequency model. If, however, there are two modes of accretion, then during the observations GX5-1 might well have been in the higher accretion rate mode (as was the case for the TENMA observations (Mitsuda, 1984)), and therefore on the normal branch, where there are no QPO's present. Mitsuda has proposed that the QPO branch is due to super-Eddington accretion rates. This together with his interpretation of the normal branch would contradict the beat frequency model. On the other hand the ideas presented in this paper require an even lower accretion rate on the QPO branch than on the normal branch, and are consistent with the beat frequency model.

The model presented above does not imply that all QPO sources have a branch of negative slope in the intensity vs hardness ratio diagram, but only those with a small value for the fastness parameter as can be seen from inequality (16). It is, however, reasonable to expect a number of these sources to show a "horizontal" branch, and this is also seen in the QPO source Cyg X-2 (Hayakawa et al., 1983).

It is not known why there should be different accretion rates, which lead to the two modes of accretion. There are several possible explanations. The companion star is thought to be evolved (van den Heuvel, 1983), and as such could have surface structures that rotate with the star, and if the system is young, so that the stellar and system rotation periods are not synchronised, this could lead to the varying accretion rate. Another possibility if the neutron star is recently formed is that the orbit could be elliptical and at different points in the orbit there are different accretion rates. Whatever the explanation may be, it is well known that the bright galactic bulge sources can show strong variations in intensity (White et al., 1985), which could be interpreted as variations in accretion rate.

The model presented above does not give a definite relation between the Alfvén radius and the accretion rate. In particular the question of how the
switching from one branch to the other occurs as the accretion rate changes is unanswered and requires a better understanding of the interaction between the accretion disc and the magnetic field of the neutron star.

4. Conclusion

By interpreting the two branches in the intensity vs hardness ratio diagram as the result of two accretion modes it has been shown that GX5-1 is a slow rotator with a period > 0.1 s. This result determines, rather than assumes, an Alfvén radius as a function of count rate, and it has been shown that this significantly differs from the relations previously used. The model requires the neutron star to have a magnetic field. The results obtained, however, are independent of the strength of that field and the value found by Alpar and Shaham (1985) and van der Klis (1985(1)) is - in terms of our model - probably not correct.

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