On the precession of accretion discs in X-ray binaries

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\section*{ABSTRACT}

In this letter recent results on the nodal precession of accretion discs in close binaries are applied to the discs in some X-ray binary systems. The ratio between the tidally forced precession period and the binary orbital period is given, as well as the condition required for the rigid precession of gaseous Keplerian discs. Hence the minimum precessional period that may be supported by a fluid Keplerian disc is determined. It is concluded that near rigid body precession of tilted accretion discs can occur and generally reproduce observationally inferred precession periods, for reasonable system parameters. In particular long periods in SS433, Her X-1, LMC X-4 and SMC X-1 can be fit by the tidal model. It is also found that the precession period that has been tentatively put forward for Cyg X-2 cannot be accommodated by a tidally precessing disc model for any realistic choice of system parameters.

\textbf{Key words:} accretion discs – binaries: close – stars: individual: SS433, Her X-1, LMC X-4, SMC X-1, Cyg X-2

\section*{1 INTRODUCTION}

Some X-ray binary systems show periodic behaviour in their light curves with periods that are much longer than the binary orbital period. In order to reproduce the long period evident in the light curve of Her X-1, Katz (1973) employed a model consisting of an accretion disc that is tilted with respect to the binary orbital plane and which is in a state of tidally forced nodal precession. In this model Katz assumed that only a narrow ring at the disc edge was tilted and precessing. Gerend & Boynton (1976) performed detailed modelling of the observational characteristics of Her X-1 by using a geometrical tilted disc model in which the disc acts as a shadowing/occulting body and as a source of optical radiation. Similarly a geometrical model has been applied to SS433 by Leibowitz (1984), who also related the problem of a precessing disc to the propagation of tidally excited bending waves. Heemskerk & van Paradijs (1989) used a geometrical tilted precessing disc model to reproduce the light curve of LMC X-4, the third X-ray binary system with a well determined long period.

Although in these models a rigidly precessing (nodally regressing) disc was found to produce light curve variations in good agreement with the observations, the issue of how a differentially rotating disc could avoid disruption through differential precession was not resolved. Papaloizou & Terquem (1995) showed that rigid body precession of a Keplerian disc is possible provided that the sound crossing timescale in the disc is small enough in comparison with the precession timescale of the disc as a whole. This analytically derived result was verified numerically by Larwood et al. (1996) through three-dimensional SPH simulations of warped precessing discs in close binaries. In that work the precession frequency, derived from linear perturbation theory for thin discs, was compared with results from the simulations. The analytical and numerical results were found to be in good agreement. Here we consider these results in the context of X-ray binary systems.

In Section 2 the analytical results are summarised and developed. In Section 3 these results are compared with observationally inferred precession periods for some X-ray binaries, and in Section 4 discussion is given. In Section 5 conclusions are presented.

\section*{2 DISC PRECESSION}

\subsection*{2.1 Basic results}

The rigid body precession frequency for a differentially rotating fluid disc can be derived from linear perturbation theory. For the leading order term in the part of the secular potential that has odd symmetry with respect to reflection in the disc midplane, the induced precession frequency $\omega_p$ is given by (Papaloizou & Terquem 1995):
\[ \omega_p = \frac{3 \, G \, M_s}{4 \, a^2} \int \frac{\Sigma \, \kappa \, \cos \delta \, dr}{\int \frac{\Sigma \, \Omega \, \cos \delta \, dr}{}}. \]  
\( \Sigma(r) \) and \( \Omega(r) \) are respectively the unperturbed axisymmetric surface density and Keplerian angular velocity profiles. The mass of the secondary (donor) star is \( M_s \), the orbital separation is \( a \), and \( \delta \) is the orbital inclination. The integrals in this equation are to be taken between the inner radius \( R_i \) and the outer radius, \( R_o \), of the disc. For a polytropic equation of state with ratio of specific heats \( 5/3 \) the rigid body precession frequency is readily calculated (Larwood 1997):

\[ \frac{\omega_p}{\Omega_o} = \frac{3}{7} \mu \left( \frac{R_o}{a} \right)^3 \cos \delta. \]  

the mass ratio is defined by \( \mu = M_s/M_p \), where \( M_p \) is the mass of the primary (compact) object. In this equation a weak radial dependence of the disc aspect ratio has been ignored (Larwood & Papaloizou 1997) and it is assumed that \( R_o \gg R_i \). This equation differs by a factor of \( \sim 2 \) from the expression for a precessing ring that was first applied by Katz (1973). The smaller coefficient found here is due to averaging of the tidal torque over the disc. Physically this corresponds to a situation in which the torque that is applied at the outer disc is transmitted over the entire disc by wave transport or by viscous stresses, or by a combination of these effects.

We shall use \( \alpha \) to denote the usual Shakura-Sunyaev dimensionless kinematic viscosity (Shakura & Sunyaev 1973), which is applied to vertically shearing motions in deriving a dispersion relation for bending disturbances in linear theory (Papaloizou & Lin 1995). The constant mean Mach number that is associated with the disc is denoted by \( \mathcal{M} \). In order for bending waves to propagate efficiently it is approximately required that \( \alpha \, \mathcal{M} < 1 \) (Papaloizou & Pringle 1983), i.e. the disc must be sufficiently thick. If this condition is satisfied then bending waves propagate at approximately one third of the midplane sound speed \( c_s \) (Papaloizou & Lin 1995) and the condition for rigid body precession to occur (Papaloizou & Terquem 1995) is that

\[ \frac{r \omega_p}{3 \, c_s} < 1, \]  
i.e. the disc crossing time for bending waves is short when compared with the precession timescale. For standard disc models the condition \( r \omega_p/c_s < 1 \) will hold everywhere in the disc provided that it is satisfied near the outer edge. If bending disturbances exist in a diffusive regime then the propagation speed of bending waves in \( r \omega_p/c_s \) should be replaced by the velocity associated with diffusion of the excited warp. An analysis of the dispersion relation for bending disturbances in the diffusive regime is given by Papaloizou & Lin (1995). In this regime the essentially acoustic propagation of bending disturbances is inhibited by the damping of vertically shearing motions. If diffusive behaviour becomes important in tidally warped discs then the result is a partial loss of internal communication. Whether the disc can precess as a unit will depend on how much of the disc is in a state of good internal communication, if this is a significant portion of the outer disc then the low angular momentum inner portions can be dragged by the outer regions. This effect occurs as a result of essentially diffusive communication between sonically-connected regions in the disc (Larwood et al. 1996).

2.2 Development

The ratio between the binary orbital period and the forced precession period is obtained from the derived precession frequency (3):

\[ \frac{P}{P_b} = \frac{3}{7} \mu \left( \frac{1}{1 + \mu} \right)^{1/2} \left( \frac{R_o}{a} \right)^{3/2} \cos \delta. \]  

The relative size of the disc and orbit can be eliminated by writing the accretion disc size as a fraction \( \beta \) of the Roche radius \( R_R \) (cf. Warner 1995), such that \( R_o = \beta R_R \), then equation (4) can be rewritten:

\[ \frac{P}{P_b} = \frac{3}{7} \beta^{3/2} \mu R_{\beta}^{3/2} \cos \delta \]  

Here the analytical approximation to the Roche radius given by Eggleton (1983) is used. With this approximation the function \( R \equiv R_R/a \) is given by:

\[ R(\mu) = \frac{0.49}{0.6 + \mu^{2/3} \ln(1 + \mu^{-1/3})}. \]  

By using (3) the condition (4) can be written in terms of the binary frequency. Hence the minimum precession period that can be supported by the disc may be determined as a function of system parameters:

\[ \frac{P_b}{P} > 3 \mathcal{M} \beta^{3/2} (1 + \mu)^{1/2} R_{\beta}^{3/2}. \]  

In the diffusive regime this is:

\[ \frac{P_b}{P} > 8 \alpha \mathcal{M}^2 \beta^{3/2} (1 + \mu)^{1/2} R_{\beta}^{3/2}. \]  

Notice that even when \( \alpha \sim 1 \), diffusive transport cannot support rigid body precession of the disc as effectively as bending waves in the non-diffusive regime. This is due to a factor \( \sim \alpha \mathcal{M} \) between the speeds associated with bending wave propagation and diffusion.

2.2.1 Disc size

In order to calculate the precession period for a system of small orbital inclination we require knowledge of the mass ratio and the disc size \( \beta \). Significant variations in \( \beta \) give rise to significant variations in the calculated period ratio, and since observations poorly constrain the disc size, it is therefore desirable to express \( \beta \) as a function of mass ratio.

As an accretion disc occupies an increasing fraction of the primary’s Roche lobe, the outer disc feels an increasing tidal torque owing to non-tidal effects. Paczyński (1977) calculated the largest periodic non-intersecting test particle orbit contained within the primary’s Roche lobe for a range of mass ratios. Paczyński argued that the accretion disc could not exist outside of this orbit, provided that pressure and viscosity were sufficiently small in the disc. Papaloizou & Pringle (1977) analysed the linearised hydrodynamic equations for azimuthal modes and calculated the tidal torque acting on the disc. They determined the radius at which streamlines intersect under the action of the component of the tidal torque with two-fold azimuthal symmetry, for a range of mass ratios.

Paczyński tabulated the dimensions of the largest test...
3 APPLICATION

Data for all the objects discussed here can be found in Table (1).

3.1 Systems with well determined periods

In this Section the formulae presented above are applied on a case by case basis to observed systems having well determined long periods (e.g. White, Nagase & Parmar 1995).

Table 1. Data used for X-ray binaries in this paper. References are given in the text.

| Source   | $M_a(M_{\odot})$ | $M_p(M_{\odot})$ | $P_p(d)$ | $P(d)$  |
|----------|------------------|------------------|-----------|---------|
| SS433    | 3.2              | 0.8              | 164       | 13.1    |
| Her X-1  | 2.3              | 1.5              | 35        | 1.7     |
| LMC X-4  | 15.7             | 1.48             | 30.5      | 1.4     |
| Cyg X-2a | –                | –                | 78        | 9.8     |
| SMC X-1  | 17.2             | 1.6              | 55        | 3.9     |

*aCyg X-2 has an estimated mass ratio of 0.34.

particle orbit for mass ratios: 0.03 $< \mu < 30$. For mass ratios $0.03 < \mu < 2/3$ it is found that the mean disc radii (hereafter “Paczyński radii”) are roughly independent of mass ratio with a mean value of approximately $\beta = 0.86$. For $2/3 < \mu < 30$ Paczyński’s values give $\beta$ as a decreasing function of mass ratio, with values in the range 0.85 – 0.6. In this case the dependence of the mean radius on mass ratio can be fit with the function:

$$\beta_p(\mu) = \frac{1.4}{1 + [\ln(1.8\mu)]^{0.24}}$$

(9)

This function fits the Paczyński radii to better than 1% for $2/3 < \mu \lesssim 15$ and to better than 3% for $15 \lesssim \mu \lesssim 30$. Hence if hydrodynamical effects can be ignored, i.e. if the disc is sufficiently thin and weakly viscous, the disc size can be determined as a function of mass ratio. This estimate for the disc size is a lower limit for accretion discs in real systems since even small amounts of gas pressure or viscosity can result in larger discs (Papaloizou & Pringle 1977).

Papaloizou & Pringle tabulated values of the disc size resulting from the two-fold symmetric component of the tidal torque for mass ratios: $0.2 < \mu < 10$. It is found that the dependence on mass ratio for these values is roughly a constant, having a mean value $\beta \approx 0.88$. It is noted that this estimate is least reliable for small mass ratios since higher order azimuthal modes can become significant in these cases, which results in a smaller disc size.

The actual truncation radii of accretion discs in close binaries will depend on the hydrodynamic properties of the disc gas. If the disc is weakly viscous and pressurised then the Paczyński radii are expected to describe accurately the disc sizes. However, if the disc is thick and/or viscous then these values may under estimate the disc size by a factor of up to $\sim 2$, for mass ratios significantly greater than unity.

3.1.1 SS433

A review of the observational characteristics of this object has been given by Margon (1984). SS433 exhibits a bipolar jet with an anti-symmetric S-curve structure. The opening angle of the S-curve is approximately 40°. The standard naive picture for this system involves a precessing disc with the precessing jet being launched normal to the disc surface and from the central regions of the disc. Within the context of this interpretation we deduce that the disc is inclined by $20^\circ$ with respect to the orbital plane of the binary.

The binary system has a mass ratio $\mu = 4$ (D’Odorico et al. 1991) and the period ratio is determined to be $P_p/P = 13$. Using these values equation (6) implies $\beta = 0.84$, which is consistent with the truncation radii calculated by Papaloizou & Pringle (1977) for gas discs. The condition (6) then indicates that in order to support the observed level of precession we require a Mach number $\mathcal{M} < 18$. Features of the long period in the photometric light curve suggest that the disc may be very thick with an aspect ratio significantly greater than 0.1 (Margon 1984), which could permit the quasi-rigid body precession of the disc under the condition given above. A further consideration is of the short period photometric variations that are thought to be due to “nodding” motions of the disc (Katz et al. 1982). The period of these variations is one half of the synodic period of the binary. It was suggested that the disc must be able to efficiently communicate with itself in order to give a coherent photometric variation and jet response to the time varying tidal torques that are applied to the outer disc. Qualitatively similar nodding behaviour was found in the numerical simulations of Larwood et al. (1996), for a disc model with an aspect ratio $\sim 0.15$.

3.1.2 Her X-1

This system has a mass ratio $\mu = 1.5$ (Reynolds et al. 1997) and a period ratio $P_p/P = 21$. In order to reproduce the observed period ratio we find approximately $\beta = 0.7$, from equation (6) for small inclination. This value is the same as the Paczyński radius, being smaller than the truncation radius expected in a gas disc (Papaloizou & Pringle 1977). The condition (6) indicates that in order to support the observed level of precession we require a Mach number $\mathcal{M} < 38$. The radiative heating model of Schandl & Meyer (1994) gives a Mach number close to this value for Her X-1. Our result is consistent with the tidal precession of a thin disc. It is noted that this situation is not in disagreement with inferences of large aspect ratios for this system since thin discs can be strongly warped with large opening angles (Larwood et al. 1996).

However there is independent evidence that the disc in Her X-1 might be quite thick. Katz et al. (1982) find evidence for nodding motions in the photometric data, and detailed modelling of the optical characteristics by Gerend & Boynton (1976) results in a model fit with an extended thick disc with a large inclination. Gerend & Boynton find $\beta = 0.77$ and $\delta = 30^\circ$. Remarkably, with these values equation (6) yields a period ratio of 21. It is not known whether a disc with such a high inclination can survive in a semi-detached system, yet it is amazing that parameters
deduced from a geometrical model for generating the light curve are consistent with the tidal model for disc precession.

### 3.1.3 LMC X-4

This is an extreme mass ratio system with \( \mu = 10.6 \) (Levine et al. 1991) and a period ratio \( P_p/P = 22 \) (Lang et al. 1981). For a small disc inclination and the expected Paczyński radius with \( \beta = 0.6 \), we find a period ratio \( P_p/P \approx 19 \). This level of precession may be supported if \( M < 48 \). As for Her X-1, we deduce a thin precessing disc for LMC X-4. It is noted that in order to match the observed period exactly we require an inclination \( \delta = 35^\circ \), or a disc size \( \beta \approx 0.5 \).

As for SS433 and Her X-1, LMC X-4 shows evidence for nodding motions (Heemskerk & van Paradijs 1989). However if this is taken as evidence of a much more extended disc then we would have to accept extreme inclinations (e.g. \( \delta \approx 60^\circ \) for \( \beta = 0.8 \)).

### 3.2 Other systems

There are few other systems reported in the literature which are known to exhibit periodic X-ray variability on long timescales and which also have known orbital periods and for which there exists an estimate of the mass ratio. Cyg X-2 and SMC X-1 are two such systems.

#### 3.2.1 Cyg X-2

This system has recently been identified to have a period ratio of \( P_p/P = 8 \) (Wijnands, Kuulkers & Smale 1996). Although the origin of this period has been tentatively proposed as resulting from disc precession the available data is at present insufficient to make detailed comparisons with the systems discussed above (Wijnands et al. 1996). The binary has a mass ratio \( \mu = 0.34 \) (Casares, Charles & Kuulkers 1998), which indicates a Paczyński radius with \( \beta = 0.86 \). Using these values implies a period ratio of 31, for small inclinations. Therefore the observed period ratio for this system cannot be reproduced for any \( \beta < 1 \), or any inclination. Also the observed period cannot be obtained by even quite large adjustments to the mass ratio (see below). The condition for rigid precession at the observed rate is also very stringent: \( M < 9 \). Assuming an accurate determination for the orbital period, it would seem very unlikely that the usual tilted precessing disc model can apply to Cyg X-2 and another explanation for the long period must be sought instead.

#### 3.2.2 SMC X-1

This system, with mass ratio \( \mu = 10.8 \) (Reynolds et al. 1993), is thought to show a period ratio \( \sim 14 \) (Wojdowski et al. 1998). For small inclinations we find that \( \beta = 0.7 \) is consistent with the observed period, being larger than the Paczyński radius with \( \beta = 0.6 \). As for SS433 a thick disc is also required here, with \( M < 25 \). This is consistent with the larger disc size than for LMC X-4, which has a similar mass ratio. Slightly more extended discs can be considered for high inclinations (e.g. \( \delta = 30^\circ \) for \( \beta = 0.77 \)).

### 4 DISCUSSION

For mass ratios \( \mu = 0.2 - 20 \), with Paczyński radii corresponding to values \( \beta = 0.9 - 0.6 \), and for small inclinations, we find period ratios for precessing tilted discs in the range \( P_p/P \approx 18 - 40 \). If the mean Papaloizou-Pringle disc truncation radius applies then the lower limit could be \( \sim 10 \). In Fig. 1 we give the period ratio for a constant \( \beta = 0.87 \) for all mass ratios, which averages the mean constant values given by the truncation models described earlier. The period ratio for \( \mu > 2/3 \) that uses the analytical fit (9) to the Paczyński radii is also plotted, as are the values given in Table (1).

Given our ignorance of the disc sizes in these systems the period ratios for SS433, Her X-1, LMC X-4 and SMC X-1 are fit reasonably well by the tidal model for disc precession. LMC X-4 is fit the worst as it appears to require an uncomfortably high inclination and/or a very small disc. However, since the mass ratios for LMC X-4 and SMC X-1 are similar, the large difference in their period ratios is probably due to differences in disc size. Therefore the hydrodynamic properties of the discs should be different, or the disc truncation process should be different, in the two systems. It is noted that wind accretion can be important in the mass transfer process in high mass ratio X-ray binaries (e.g. Frank, King & Raine 1985). The slow stellar winds that are thought to exist in LMC X-4 and SMC X-1 (Hammerschlag-Hensberge, Kallman & Howarth 1984) favour the formation of small discs (e.g. Theuns & Jorissen 1993), however the effect of stellar winds on the truncation of a viscously expanding disc is not known. The smaller orbital separation in the LMC X-4 system would appear to be consistent with the idea of wind-driven truncation of the discs.

In the simulations of Larwood et al. (1996) the precession periods of the simulated discs were found to be \( \sim 10\% \) longer than the expected values when the discs were moderately thin, i.e. when the level of internal communication of the disc was relatively poor. It is of interest to note that SS433 appears to be in a state of good internal communication and we infer a disc size comparable to that expected for gas discs. LMC X-4 requires a comparatively small disc, although larger discs could reproduce the required preces-
ession rates by a modest relaxation of internal communication in the disc. This is reasonable since the larger period ratio for LMC X-4 permits a thinner disc than for SS433, and so may marginally satisfy $\alpha M > 1$.

Fig. 1 shows that for $\mu > 1$ the period ratio is not a sensitive function of mass ratio. Hence for the systems considered above, the most important effects for modifying the expected period ratios are loss of internal communication and changes to the disc size. It is also noted that the $\lesssim 10\%$ fluctuations that are often seen in the precession periods of the objects discussed here can be accommodated by the tidal model by assuming small fluctuations in the disc size, perhaps due to time dependent tidal torques that cause time varying distortions to the envelope of the outer disc. In this case fluctuations in the precession rate should be minimised for the smallest discs.

5 CONCLUSIONS

On a case by case basis the analytical results for the tidally induced precession of tilted accretion discs agree reasonably well with observationally inferred period ratios for SS433, Her X-1, LMC X-4 and SMC X-1. The results for SS433, Her X-1 and SMC X-1 are consistent with inferences of thick discs that occupy a substantial fraction of the Roche lobe radius. This is encouraging for the current model since thick discs are expected to allow the propagation of bending waves over much of the disc, and so enable its quasi-rigid body precession despite Keplerian shear. It is noted that in the diffusive regime the maximum Mach numbers quoted above may be smaller by a factor of $\sim \alpha M$. If those discs have $\alpha M$ significantly greater than unity then we would need extreme disc thicknesses, and therefore the precessing disc model might become untenable in terms of rapidly communicating across the disc a precessional torque that is essentially applied to the outer regions. Unfortunately there are currently no unambiguous observational constraints on the disc thickness in any of these systems.

LMC X-4 is not fit so well as the other systems, but its extreme mass ratio and its short orbital period may require a different disc formation mechanism than was supposed here. If wind accretion becomes important as a mass transfer process then the disc size is generally smaller than that which results from standard Roche lobe overflow. If the disc remains small (perhaps owing to the incident stellar wind from the secondary) then the period ratio in LMC X-4, and other extreme mass ratio systems, may be larger than predicted from theory given only knowledge of the mass ratio. In this case the disc would not necessarily need to be thin, as is required here to account for the small disc size that is needed to give the observed precession rate.

For mass ratios greater than about 2/3 the disc size is not well constrained by theory (we expect $0.9 > \beta > \beta_{\nu}$). Therefore in order to make a stronger comparison with the observations requires further observational input on the sizes of the discs in these systems.

The precession period that has recently been attributed to Cyg X-2 cannot be due to a simple tidally precessing tilted disc model because the long period for that system is much too short, even if the mass ratio is very much larger than currently believed. It is expected that quasi-rigid body precession of the disc at the observed rate cannot be supported by the disc whatever the origin of the precessional torque acting on the outer disc.

In this paper we have not confronted the all important issue of an origin for the disc tilt. Several mechanisms for either setting up inclined discs, or allowing for small tilts and warps to grow, have so far been proposed. In the context of a tidal model, Papaloizou & Terquem (1995) deduced that the secular response of the disc allows for the disc inclination to increase by significant amounts over a viscous timescale. Radiative torques have also been put forward as a possible origin for warping and precession in X-ray binaries (Maloney & Begelman 1997). This model involves applying the precessional torque at the outside of a cold disc, and communicating it throughout the disc by diffusive effects alone. As indicated above, even if $\alpha \sim 1$ it seems unlikely that very thin discs could survive precession at the observed rates. This process has yet to be studied in the non-diffusive regime.

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