XTE J1118+480: Clues on the Nature of the Accretion Flow from the Optical Variability

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Abstract. We show how the simultaneous presence of a strong quasi periodic oscillation (QPO) of period $\sim 10$ seconds in the optical and X-ray lightcurves of the X-ray transient XTE J1118+480 can be used to obtain information about the nature of the accretion flow around the source. The unusually high optical-to-X-ray flux ratio and the QPO observed simultaneously in both energy bands suggest that a significant fraction of the optical flux might originate close to the central source, where most of the X-rays are produced and be indicative of a magnetically dominated corona. We also show how the temporal evolution of the QPO can provide us with information on both the inner radius and the viscous properties of the optically thick accretion disc.

Keywords: accretion discs - magnetic field - stars: individual: XTE J1118+480

1. Introduction: The Magnetic Corona Model

The transient X-ray source XTE J1118+480 was discovered with the RXTE All-Sky Monitor on March 29, 2000 (Remillard et al. 2000). At the peak of its outburst, it showed an X-ray spectrum typical of black hole candidates (BHC) in their hard state, with a prominent power-law component (photon index of about 1.8). The 13th magnitude optical counterpart, discovered by Uemura, Kato & Yamaoka (2000), exhibited a spectrum fairly typical of X-ray Novae in outburst (Dubus et al. 2000 and references therein). A strong QPO with frequency $\nu_{\text{QPO}} \sim 0.1$ Hz has been found in the X-ray power density spectrum (PDS) of the source (Wood et al. 2000); more surprisingly, the optical lightcurves also showed a prominent QPO at the same frequency (Haswell et al. 2000). The QPO frequency drifted to higher values systematically in both bands for about two months.

As discussed in detail in Merloni, Di Metteo & Fabian (2000) (MDF), the high optical-to-X-ray flux ratio and the optical/UV variability argues for the presence of significant cyclo-synchrotron (CS) radiation from active regions in a magnetically dominated corona in this source. Assuming that a fraction of the observed optical flux corresponding to

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its oscillating part ($\sim 30\%$) is due to CS emission from a magnetized corona, we modeled the spectrum taking into account reprocessing of coronal radiation in the accretion disc (according to the height of the active regions) and all the relevant radiative processes (see MDF for details). The disc was assumed to extend down to the innermost stable orbit of a non-rotating black hole ($R_{\text{in}} = 6GM/c^2 = 3R_\text{S}$). We found that, in order to match the high (compared to X-rays) optical flux, both a low accretion rate ($\dot{M}/\dot{M}_{\text{Edd}} = \dot{m} \approx 0.01$), and a high fraction of accretion power dissipated in the corona ($f > 0.9$) are needed; also the active regions need to be high above the disc (at about $10R_\text{S}$).

Hynes et al. (2000) reporting on EUVE observations of the source showed that the low measured EUV flux is inconsistent with an optically thick disc extending down to radii $R < 1000R_\text{S}$ (but see Dubus et al. 2000 for a different estimate of the EUV flux). Based on this, they favor an inner advection-dominated flow (ADAF) surrounded by a geometrically thin disc truncated at hundreds of $R_\text{S}$. In the next section we show how to use the variability information to put constraints on the inner disc location.

2. The QPO Viscous Evolution

Beside the peaked QPO around 0.1 Hz, the observed PDS of XTE J1118+480 exhibits a broader feature around 1 Hz; plotted one against the other, these frequencies fall remarkably well on the correlation among QPOs discovered by Psaltis, Belloni & van der Klis (1999) in the PDS of BHC and neutron stars. Such a correlation is likely to reflect a general property of the accretion flows around these objects. Here we assume that the QPO observed in XTE J1118+480 is produced at a specific distance ($R_t = r_1R_\text{S}$) where a discontinuity of the flow occurs, as in Psaltis & Norman (2000). The QPO frequency must be essentially determined by the relativistic dynamical frequencies of the system (Psaltis & Norman 2000; Stella, Vietri & Morsink 1999).

XTE J1118+480 observations offer the opportunity to track the QPO evolution over a long period of time (Wood et al. 2000). To model such evolution, we calculate $R_t(t)$ integrating the equation of the viscous evolution of a standard Shakura-Sunyaev disc:

$$\frac{\partial R_t}{\partial t} = - \frac{3}{2} \alpha \left( \frac{H}{R_t} \right)^2 \left( \frac{GM}{R_t^3} \right)^{1/2} J^{-1},$$

Alternatively, a good agreement with the data could be achieved if the active regions move relativistically away from the disc (MDF, see also Markoff, Falcke & Fender 2000 for a jet model of the SED).
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(a) \( \nu_{QPO} = 2 \nu_{LT} \); rad. p.: \( \chi^2 / \text{dof} = 0.21 \);
\( \alpha \dot{m} (1 - f) \)^2 \( \simeq 4.5 \times 10^{-8} a^{7/6} m^{-1/6} \)

(b) \( \nu_{QPO} = \nu_{Kepler} \); gas p.: \( \chi^2 / \text{dof} = 0.80 \);
\( \alpha^{4/5} \dot{m}_m (1 - f)^{1/5} \simeq 2.5 \times 10^{-4} m^{4/15} \)

Figure 1. Fit to the observed QPO evolution (RXTE and USA data, Wood et al 2000) for (a) a QPO produced by relativistic LT precession in a radiation pressure dominated disc and (b) a QPO produced by modulation with Keplerian frequency in a gas pressure dominated disc. The error bars are given by the QPO FWHM, which is likely to reflect the uncertainties in the location where the oscillations are excited. In the inset the ASM lightcurve of XTE J1118+480 (triangles): the continuous line is a SPLINE fit to its smooth variation (flares are excluded), which is assumed to reflect long term variations of the total accretion rate.

where \( J = 1 - \sqrt{3/r_t} \), \( \alpha \) is the viscous parameter and the disc scaleheight
\( H/R_t \simeq 9 \dot{m} J (1 - f) r_t^{-1} \) for a radiation pressure dominated disc and
\( H/R_t \simeq 0.02 (am)^{-1/10} (\dot{m} J)^{-1/5} (1 - f)^{-1/10} r_t^{1/20} \) for a gas pressure dominated one (Merloni, Fabian & Ross 2000). We test two different hypothesis on the origin of the QPO (and the accretion flow geometry):

(a) According to the relativistic precession interpretation of the observed correlation (obeyed by XTE J1118+480) \( \nu_{QPO} = 2 \nu_{nod} \simeq 1.62 \times 10^4 (a/m) r_t^{-3} \) Hz, implying \( r_t \sim 50 (a/m)^{1/3} \) (\( a \) is the BH angular momentum, \( m \) its mass in Solar mass units). In this case the radiation pressure solution, appropriate for the inner part of an optically thick disc, should be used in Eq (1).

(b) Alternatively, the observed low frequency QPO can be due to a Keplerian modulation of the flow: \( \nu_{QPO} = \nu_{Kepler} \simeq 1.14 \times 10^4 m^{-1} r_t^{-3/2} \) Hz, so that \( r_t \sim 2000 m^{-2/3} \), and the gas pressure solution must be used in this case.

Furthermore, we assume that the smooth variations of the X-ray ASM luminosity reflects a modulation of the total accretion rate so that
\( \dot{m}(t) = g(t) \dot{m}_0 \), where \( g(t) \) is the continuous function shown in the inset in Fig. 1. We integrate Eq. (1) and fitted the temporal evolution of the QPO frequency with the resulting \( v_{QPO}(R(t)) \) for the two cases and show the results in Fig. 1. Both fits are acceptable, but the relativistic precession model (with \( r_t = O(10) \)) explains the QPO evolution better than the Keplerian one (with \( r_t = O(1000) \)). Finally, from such fits we can obtain an estimate of the viscous parameters of the optically thick accretion disc (\( \alpha, \dot{m}, f \), through the products shown in Fig. 1) independent on any spectral analysis. The estimate from MDF (\( \dot{m} f \approx 10^{-3} \)) based on the magnetic corona model is also consistent with case (a) (with \( \alpha \approx 0.01 \)), while for case (b) it would imply an unreasonably low viscosity.

3. Conclusions

The main rationale for our model is the simultaneous presence of a strong QPO in the optical and X-ray lightcurves of XTE J1118+480, suggesting that the fluxes in the two bands both originate from the same region in the inner part of the accretion flow. Self-absorbed CS emission is the natural candidate to explain the optical variability. Such emission is expected in any magnetic corona model, and the inferred magnetic field value (\( B \approx 2 \times 10^6 \) G) is the one predicted to arise when the source is in the hard state (MDF). We have also shown how the evolution of the QPO can be satisfactorily accounted for if the QPO is produced by a modulation whose frequency is equal to twice the relativistic nodal precession in a radiation pressure dominated disc and the location of such modulation (that is perhaps where the inner accretion disc undergoes a transition and is at most a few tens of Schwarzschild radii) viscously drift inwards.

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