On the nature of pulse profile variations and timing noise in accreting millisecond pulsars, or

How to see invisible

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+ Askar Ibragimov, Marja Annala
Spectral energy distribution

Poutanen & Gierlinski (2003).

Comptonization
$T_e = 50-90$ keV, $\tau_T \sim 1$

black body
0.7 keV

reflection

Energy, keV

$E_F E \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$

Normalized Flux

SAX J1808.4–3658

Phase
Timing noise: residuals

XTE J1807-294

XTE J1751-305

XTE J1814-338

SAX J1808.4-3658

A. Patruno
Variations of pulse phases and amplitudes

\[ F(\phi) = \bar{F}\{1 + a_1 \cos[2\pi(\phi - \phi_1)] + a_2 \cos[4\pi(\phi - \phi_2)]\}\]

Ibragimov & Poutanen 2009
Pulse profile is stable during high flux level and varies in the end of the outburst.

Spot wandering? Secondary spot is visible?

Accretion disk recedes from the star?

Hartman et al. (2008)
Ibragimov & Poutanen (2009)
Evidence for a receding disk

Reflection - flux correlation
Reflection tells what is the solid angle occupied by the accretion disk as viewed from the hotspot.

Flux drops, reflection drops $\Rightarrow$ disk is moving out
SAX J1808 in October 2008

Global pulse profile
fundamental
2nd harmonic

Fractional amplitude [% rms]

Energy [keV]

Patruno et al. 2009
Spectral energy distribution

constant oscillates

Poutanen, Patruno et al., in preparation
Inner disk radius at the moment of secondary spot appearance

\[ R_{\text{disk}} = 26 \pm 8 \text{ km} \]

for \( 50 \leq i \leq 70 \text{ deg} \)
Neutron star magnetic field and magnetosphere-disk interaction

\[ R_m = \left( \frac{B_0^2 R_{ns}^6}{2 \dot{M} \sqrt{2GM}} \right)^{2/7} \]

At the moment of secondary spot appearance, we measure the luminosity \( \Rightarrow \) accretion rate \( \Rightarrow \) B-field

\[ \mu_{25} = (9 \pm 5) \ k_A^{-7/4} \ G \ cm^3 \]
\[ B_0 = (0.8 \pm 0.5) \ 10^8 \ k_A^{-7/4} \ G \]
\[ k_A = R_{disk}/R_m \]

Consistent with the results obtained from the spin-down of the source by Hartman et al. (2008)

\[ \mu_{25} = (5 \pm 3) \ G \ cm^3 \Rightarrow 0.8 \leq k_A \leq 2.5 \]
MHD simulations of accretion on to an inclined dipole

Romanova et al. 2004
Pulse profiles as a function of inner disk radius
Pulse phases and amplitudes for varying inner disk radius

\[ F(\phi) = \overline{F}\{1 + a_1 \cos[2\pi(\phi - \phi_1)] + a_2 \cos[4\pi(\phi - \phi_2)]\} \]
Summary

• Timing noise and phase jumps can be caused by inner disk radius variations and changing visibility of the secondary spot

• Variations of reflection ⇒ varying inner radius of the accretion disk

• RMS(E) ⇒ presence of the disk

• Change of the pulse profile ⇒ appearance of the 2nd spot ⇒ disk radius ⇒ B-field

• The pulse profile variations allow us to understand the geometry of accretion and to put constraints on the disk-magnetosphere interaction models.