Two-dimensional simulations of neutron star spreading layers

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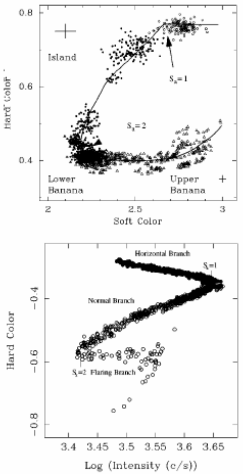
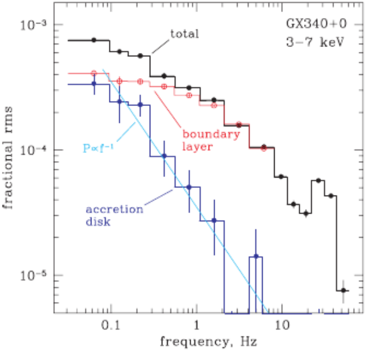
Motivation for the study: importance of the BL

"Atoll" and "Z" sources



Variable contribution from the BL



Revnivtsev et al. (2003, 2006)

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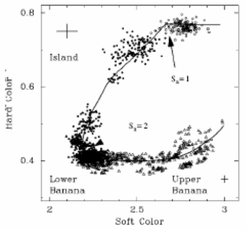
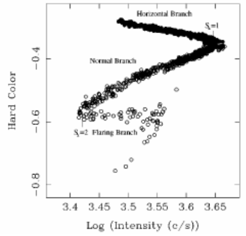
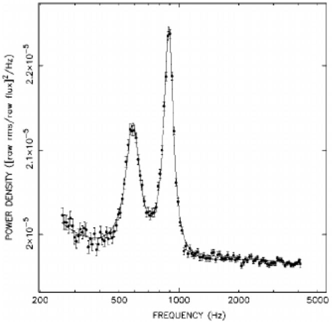




Multiple QPOs at low (Hz to hHzs) and high ($\sim 1\mathrm{kHz}$) frequencies



Sco X-1; van der Klis (any year, especially 2000)

Motivation for the study: kHz QPOs and correlation time scales

kHzQPO frequency as a function of flux:

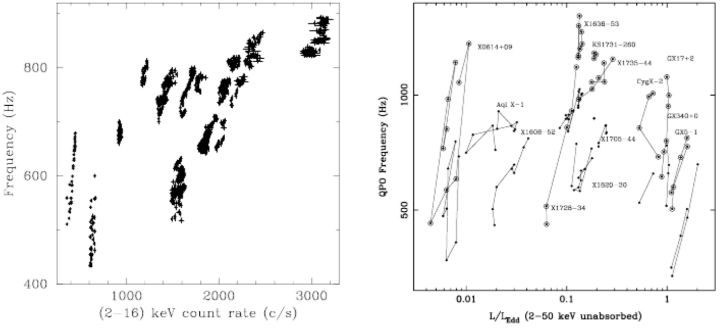


FIG. 1.—*Left*: Lower kHz QPO frequency vs. count rate in 4U 1608–52, showing the "parallel lines" phenomenon as it occurs in a single source, after Méndez et al. (1999). *Right*: kHz QPO frequencies vs. X-ray luminosity in 13 different sources, showing the parallel lines phenomenon across sources, after Ford et al. (2000).

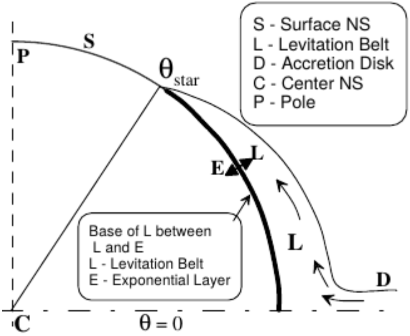
van der Klis (2006)

Motivation summary

- BL is visible
- BL is variable
- BL retains its structure (f_{kHzQPO} – flux relation) on time scales minutes to hours, much longer than the scales of the inner disc or local thermal time scales
- $\Rightarrow$spreading layer weakly coupled with both the disc and the NS

Spreading layer approximation

Spreading layer:



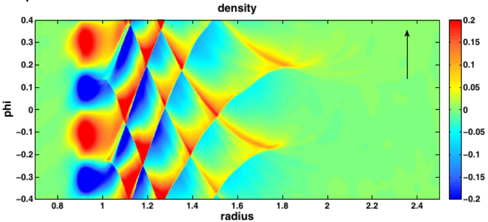
Inogamov& Sunyaev (1999, 2010), Suleimanov & Poutanen (2006)
Need to set mixing/friction by hand or go to 2D/3D.

But:

- surface friction should be small
- BC or matter source at the equator?

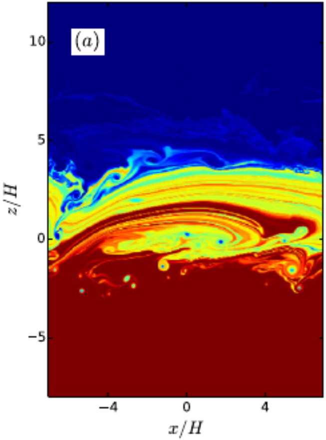
BL simulations

$R\varphi$



Belyaev, Rafikov, and Stone (2012) ;
Belyaev and Quataert (2018)
Velocity discontinuity $\Rightarrow$shear instability.
Inefficient in BL-disk angular momentum exchange.

$R\theta$



Philippov et al.(2016)

2D spectral approach

Simulation setup:

- Decomposition into spherical harmonics (`shtns` library for python)
- pseudo-spectral approach with filtering
- `https://github.com/pabolmasov/SLayer`
- goals: trace angular momentum transfer (shear instability!) and variability patterns

System of equations:
continuity

$$\frac{\partial \Sigma}{\partial t} = -\nabla \cdot (\Sigma \boldsymbol{v}) + S^{+} - S^{-}, \quad (1)$$

vorticity

$$\frac{\partial \omega}{\partial t} + \nabla \cdot (\omega \boldsymbol{v}) = -\nabla \times \frac{\nabla \Pi}{\Sigma} + \text{source/sink}, \quad (2)$$

divergence

$$\frac{\partial \delta}{\partial t} = [\nabla \times (\omega \boldsymbol{v})]_r - \nabla^2 \left(\frac{v^2}{2} + \Delta\Phi \right) - \nabla \cdot \left(\frac{1}{\Sigma} \nabla \Pi \right) + \text{sou} \quad (3)$$

energy

$$\frac{\partial E}{\partial t} + \nabla \cdot (E \boldsymbol{v}) = -\delta \Pi + Q^{+} - Q^{-} + Q_{\mathrm{NS}} + Q_{\mathrm{acc}}. \quad (4)$$

Sub-sonic case

- KH stability depends on velocity gradients
- sonic modes
- heating where different velocities are mixed ⇒sometimes RT unstable
- rapid rotation near the SL boundary

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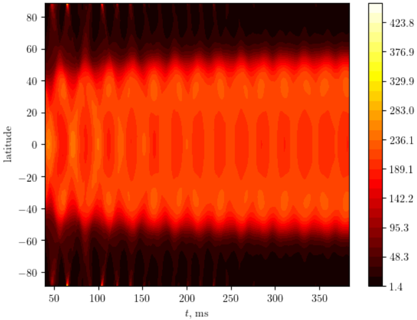
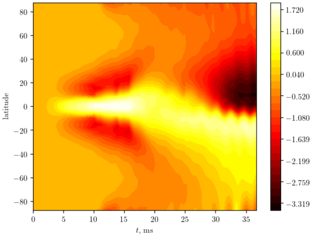


time-latitude diagram for angular frequency

Heating instability (setup-dependent)

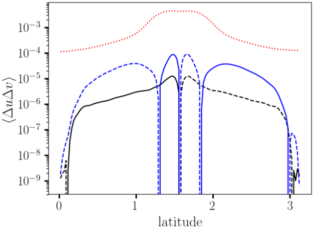
super-sonic case, Keplerian rotation, $\dot{M} = 10^{-8}\ \mathrm{M_\odot\ yr^{-1}}$



time-latitude diagram for surface density

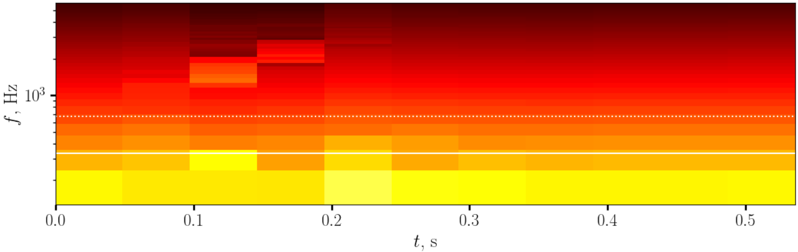
Shear instability and oblique waves

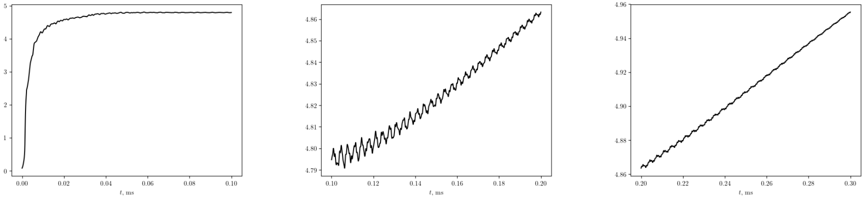
Enhanced accretion solution ($\Sigma_0 = 10^8 \mathrm{g\,cm^{-2}}$, $\dot{M} = 10^{-3}\ \mathrm{M_\odot\,yr^{-1}}$)
Reynolds's stress:



velocity correlation, mean values $v_\varphi v_\theta$, and c_s^2

Power density spectra





1D-model

(net angular momentum conservation is still an option…)

Angular momentum transfer:

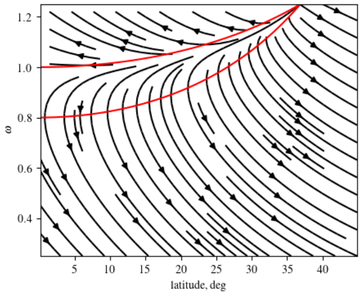
$$\dot{M}j = 4\pi R^2 \sin^2\theta R_{\theta\varphi} + \dot{M}j_0, \quad (5)$$

Energy balance:

$$\frac{cg_{\rm eff}}{\varkappa}(1-\beta) = R_{\theta\varphi}\frac{\partial\Omega}{\partial\theta}. \quad (6)$$

$\Rightarrow$

$$\frac{\partial\omega}{\partial\theta} = \frac{(1-\beta)\sin^2\theta}{\dot{m}}\frac{1-\omega^2\sin^2\omega}{\omega_0-\omega\sin^2\theta}. \quad (7)$$



Conclusions

- spectral simulations in a super-sonic regime are challenging but possible and provide a useful framework for further applications
- shear supersonic instabilities allow angular momentum transfer inside the SL (Reynolds's stress)
- non-linear evolution leads to quasiperiodics
- why $10^8\,\mathrm{g\,cm^{-2}}$?