Disk Accretion in the Propeller Regime

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Collaborators

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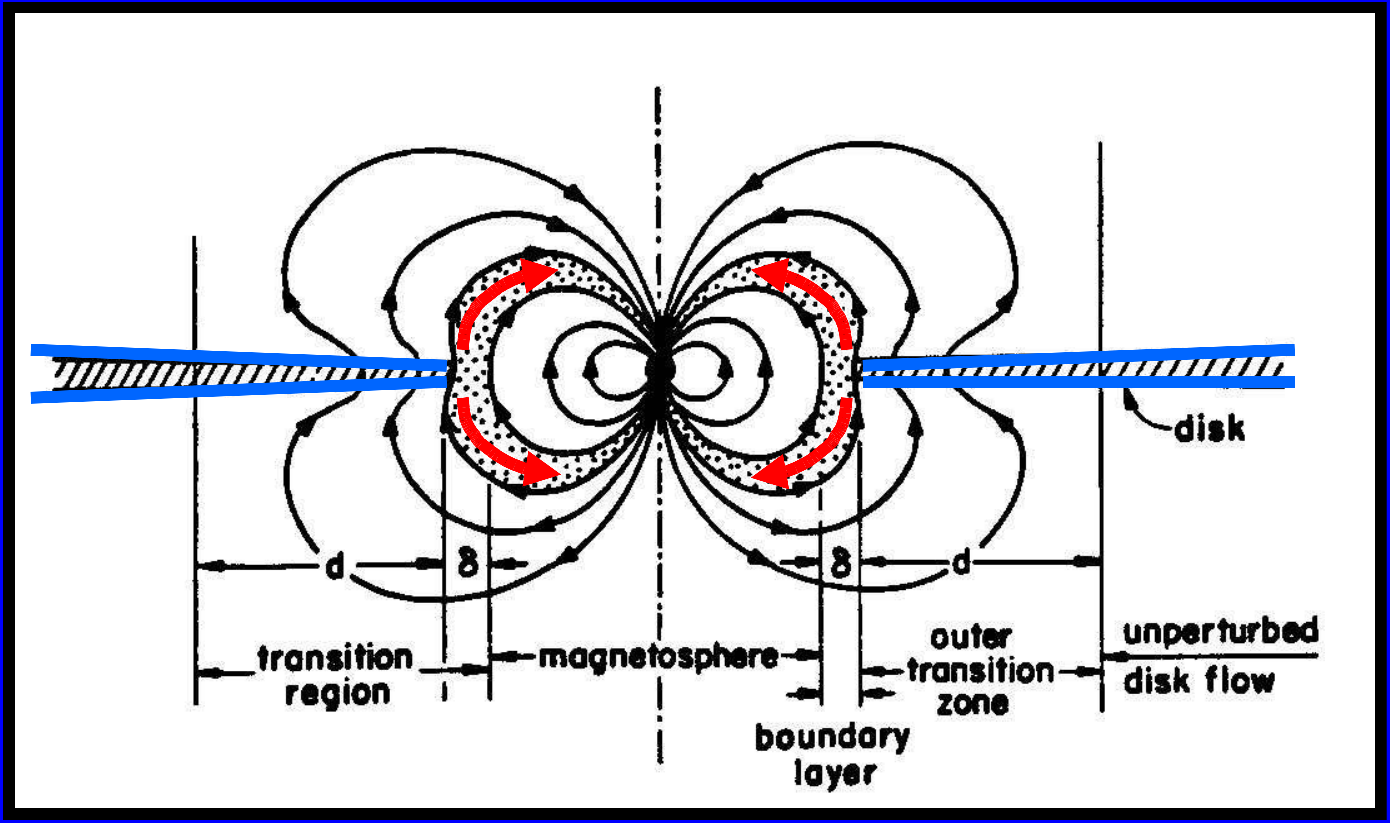
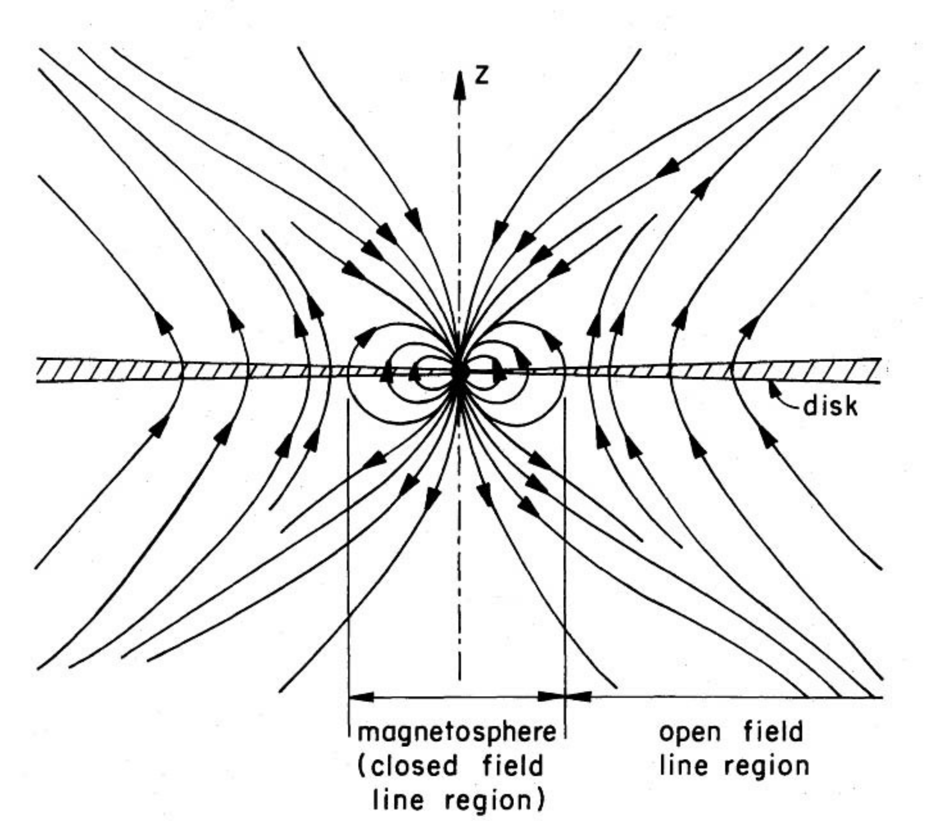
Disk-magnetosphere interaction



Pringle & Rees (1972); Ghosh & Lamb (1978-79)

Inflation of the field lines :

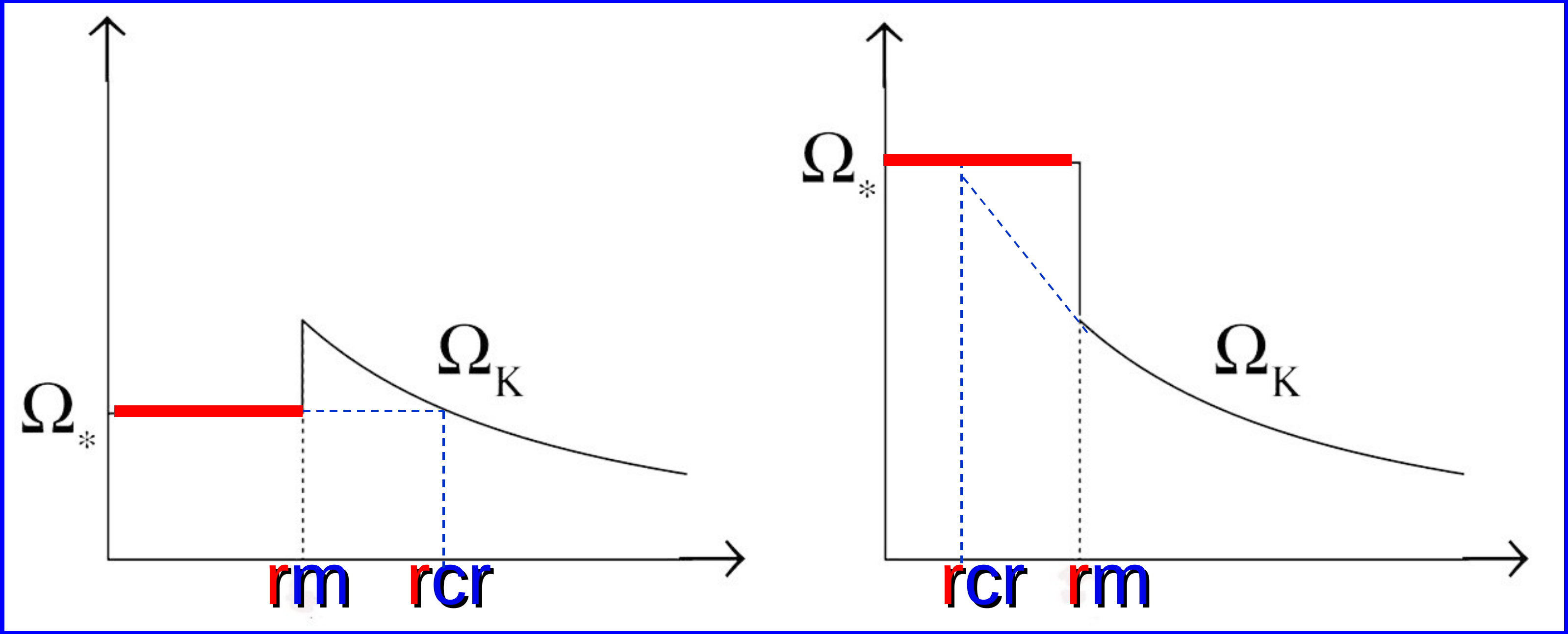


Lovelace, Romanova & Bisnovatyi-Kogan 1995
Aly 1985; Aly & Kuijpers 1990

Two main possibilities:

Slow rotation

Fast rotation



Accretion

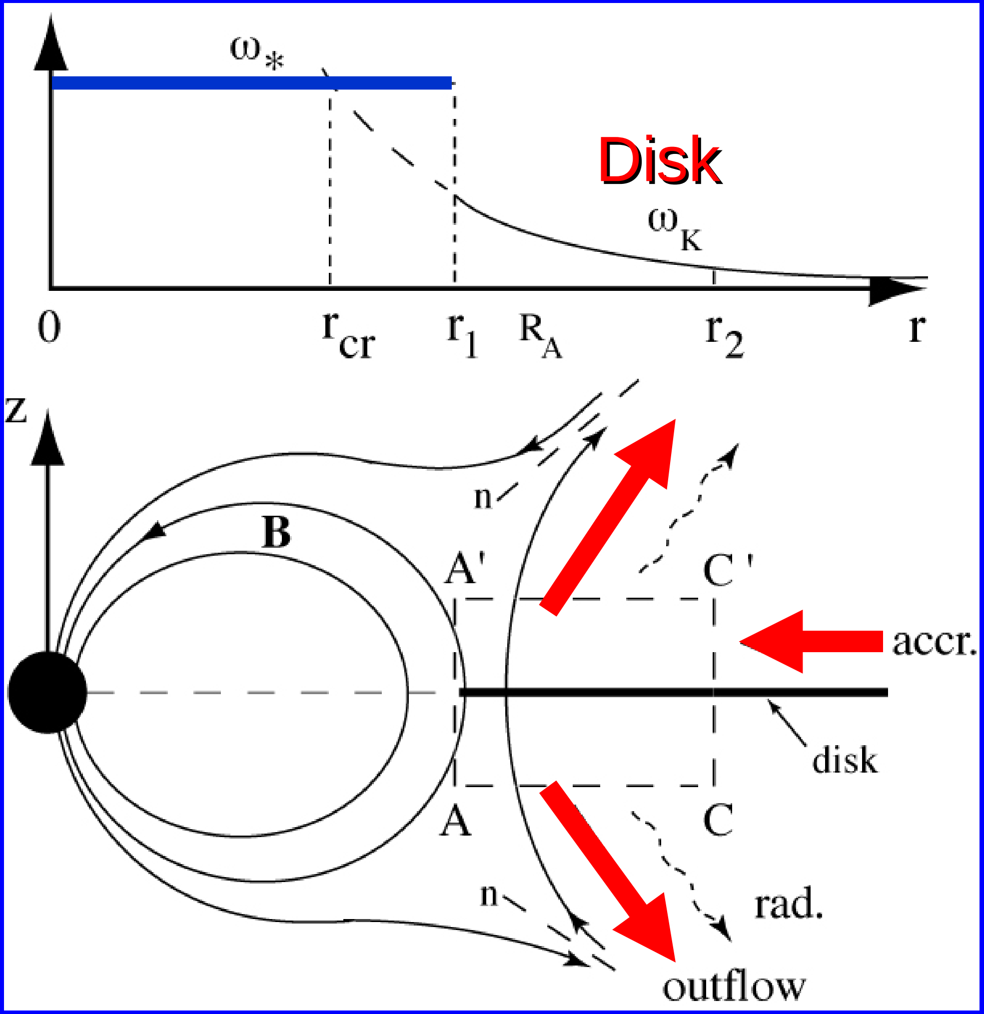
$r_{cr} > r_m$

“Propeller” regime

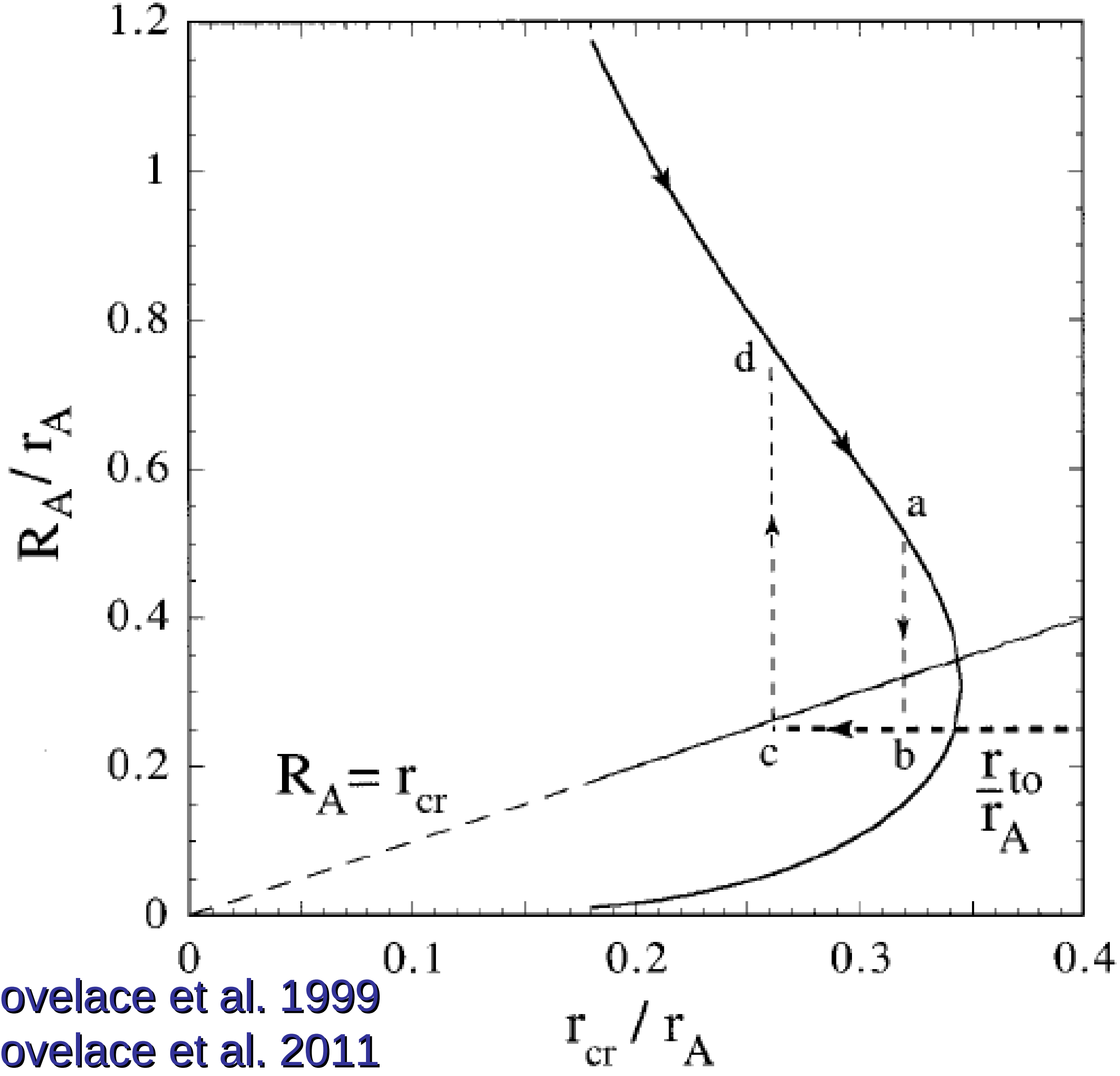
$r_{cr} < r_m$

Propeller regime

- $r_{cr} < r_m$
- $F_{cf} > F_G$


Disk

Lovelace, Romanova & Bisnovatyi-Kogan (1999) Illarionov & Sunyaev (1975)



Lovelace et al. 1999
Lovelace et al. 2011

Numerical Simulations

- 2D and 3D simulations
- Non-relativistic MHD
- Godunov-type numerical scheme
- 2D: viscosity and diffusivity
- 3D: viscosity
- Developed quasi-stationary initial conditions

Few groups performed 2D simulations of the disk-magnetosphere interaction, but in non-stationary regime:
Hayashi, Shibata & Matsumoto 1996; Miller & Stone 1997; Goodson, Winglee, & Bohm 1997, 1999

Viscosity

The average value of the viscous stress is a part of the integral gas pressure in the disk
(Shakura & Sunyaev 1973).

$$\tau = \alpha \Pi = \alpha \int p dz$$

$$\alpha \sim 5 \times 10^{-3} - 0.6$$

$$\nu_t = \frac{\alpha c_s^2}{\Omega_K} = \alpha c_s h$$

α = 5 x10-3 – 0.6

Balbus 2003, Hawley & Stone –
MRI simulations

Magnetic Diffusivity

Magnetic diffusivity may be determined by the same process as viscosity: magnetic turbulence (Bisnovatyi-Kogan & Ruzmaikin 1976, Parker 1979)

$$\nu_t = \alpha_{\rm vis} c_s h$$

$$\eta_m = \alpha_{\rm dif} c_s h$$

where $\alpha_{\rm vis}$ is α-coefficient of magnetic diffusivity

2D

3D

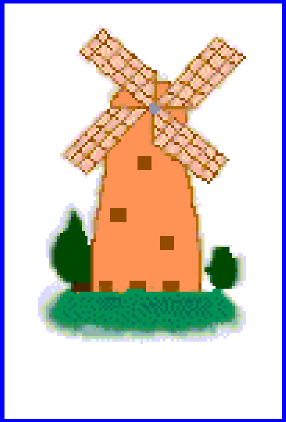
αvis=0.01-1   αdif=0.01-1

2D

Two types of propellers:

(1) “weak” propellers:
no outflows

(2) “strong” propellers:
with outflows

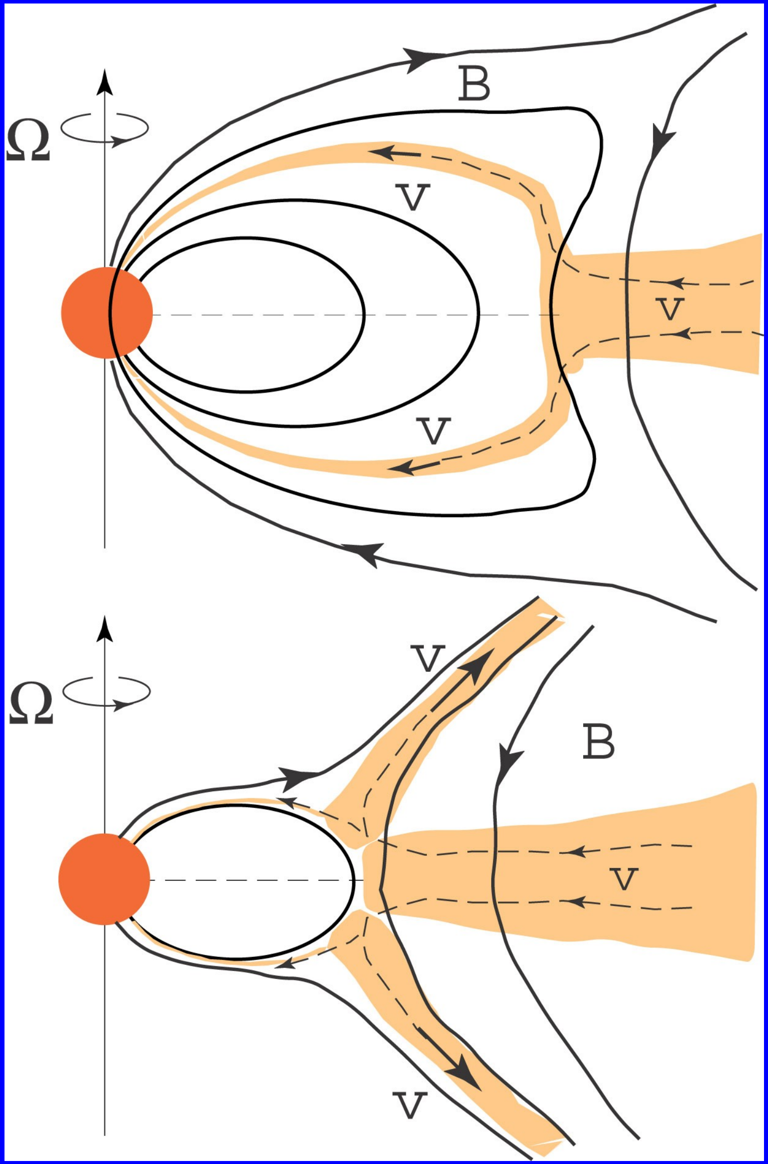


“Weak” propeller:

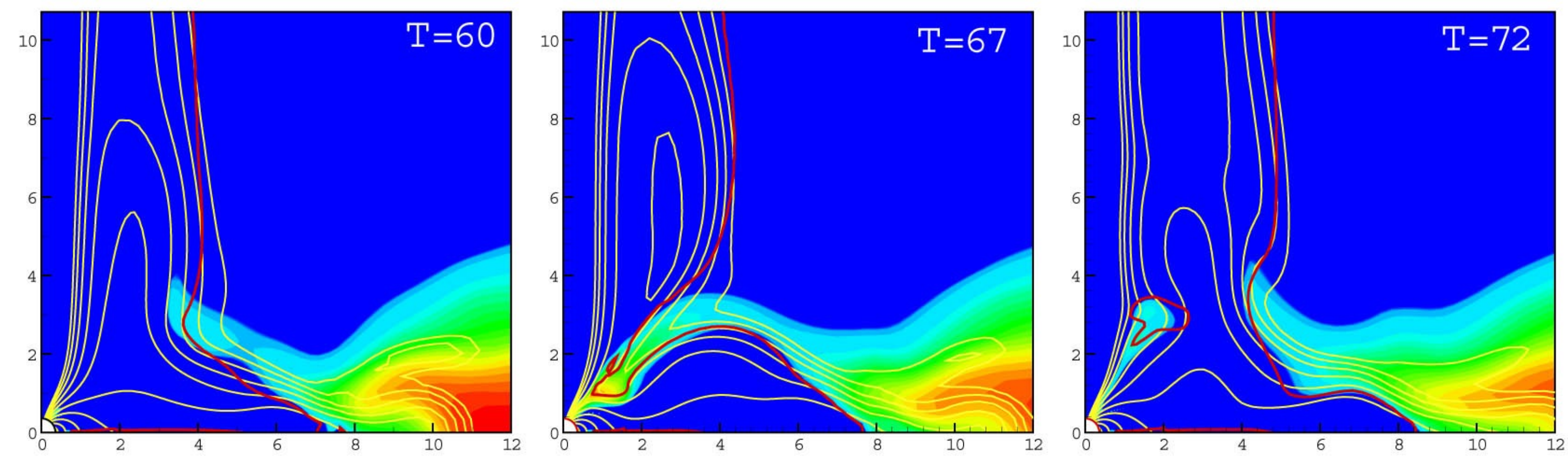
- Low accretion rate
- Small viscosity / diffusivity
- Star spins-down
- Weak or no outflows

“Strong” propeller:

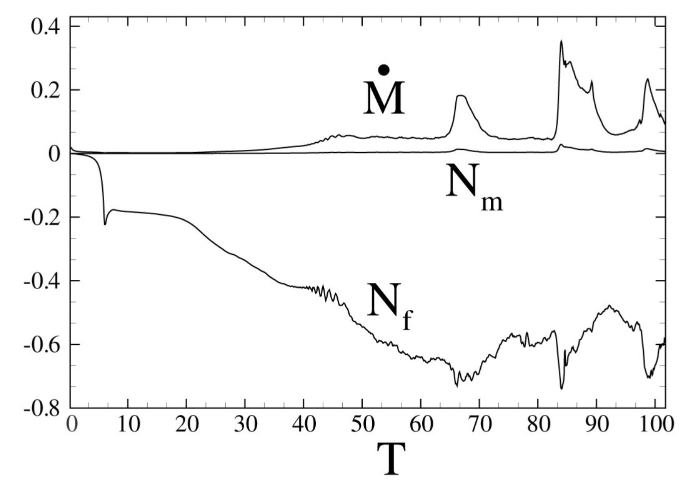
- High accretion rate
- High viscosity / diffusivity
- Matter penetrates to the region of fast rotating magnetosphere
- Strong outflows



Matter accretes to the star quasi-periodically

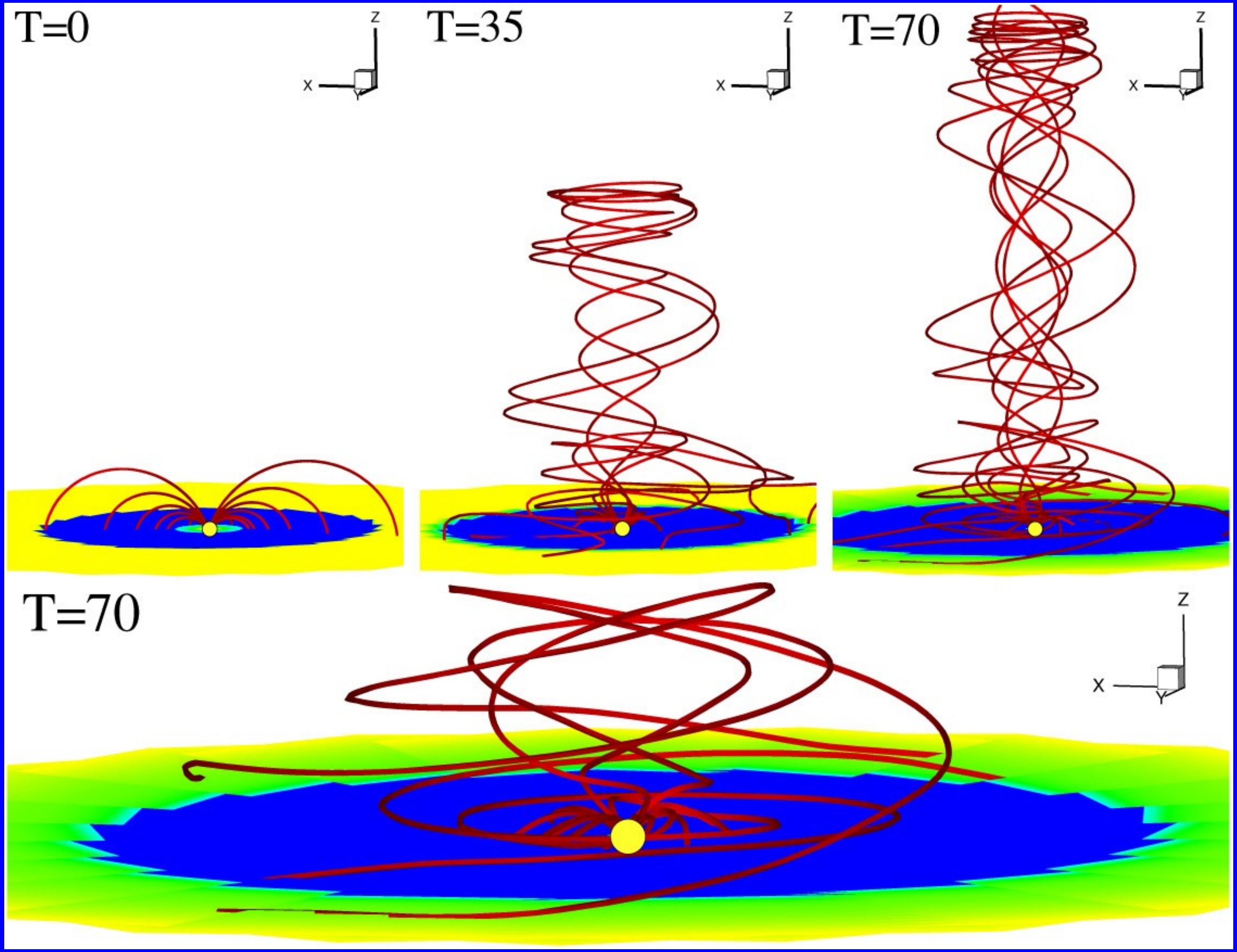


- Matter accumulates near magnetopause
- Accretes to the star through reconnection
- Accumulates again
- Star spins-down all the time



Romanova, Ustyugova, Koldoba & Lovelace (2004)

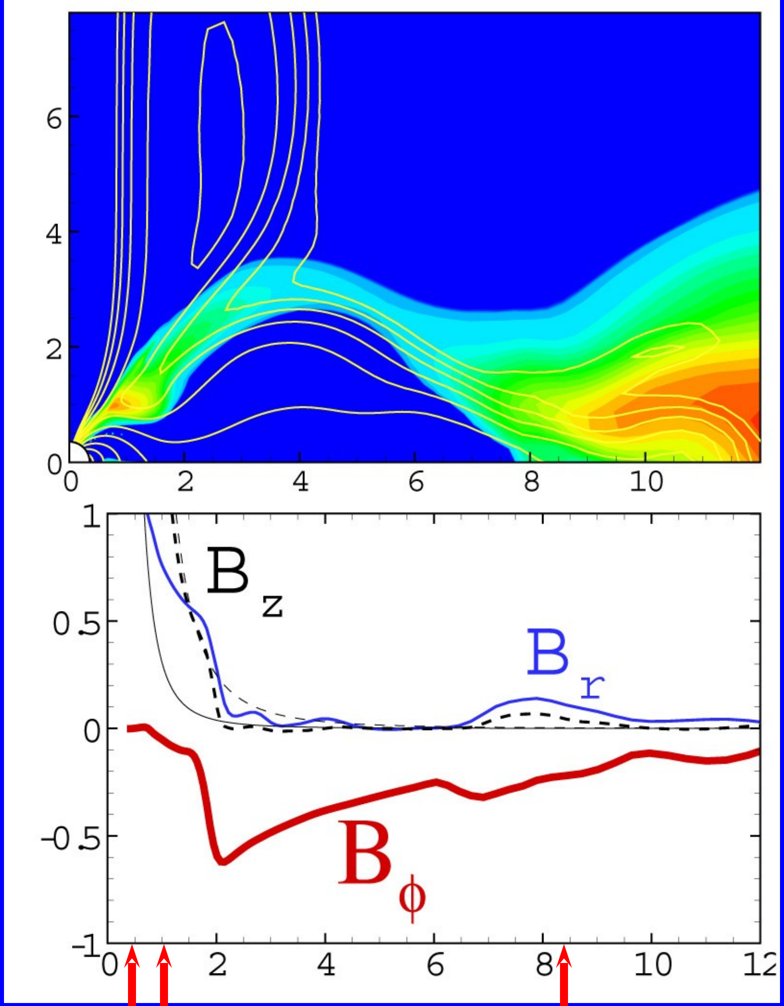
Magnetic field lines expand up, forming a “tower”



Romanova, Ustyugova, Koldoba & Lovelace (2004)

Physics of “Weak” Propellers

Magnetic field becomes non-dipole



Bϕ – component dominates

rcr rm

rm(expanded)

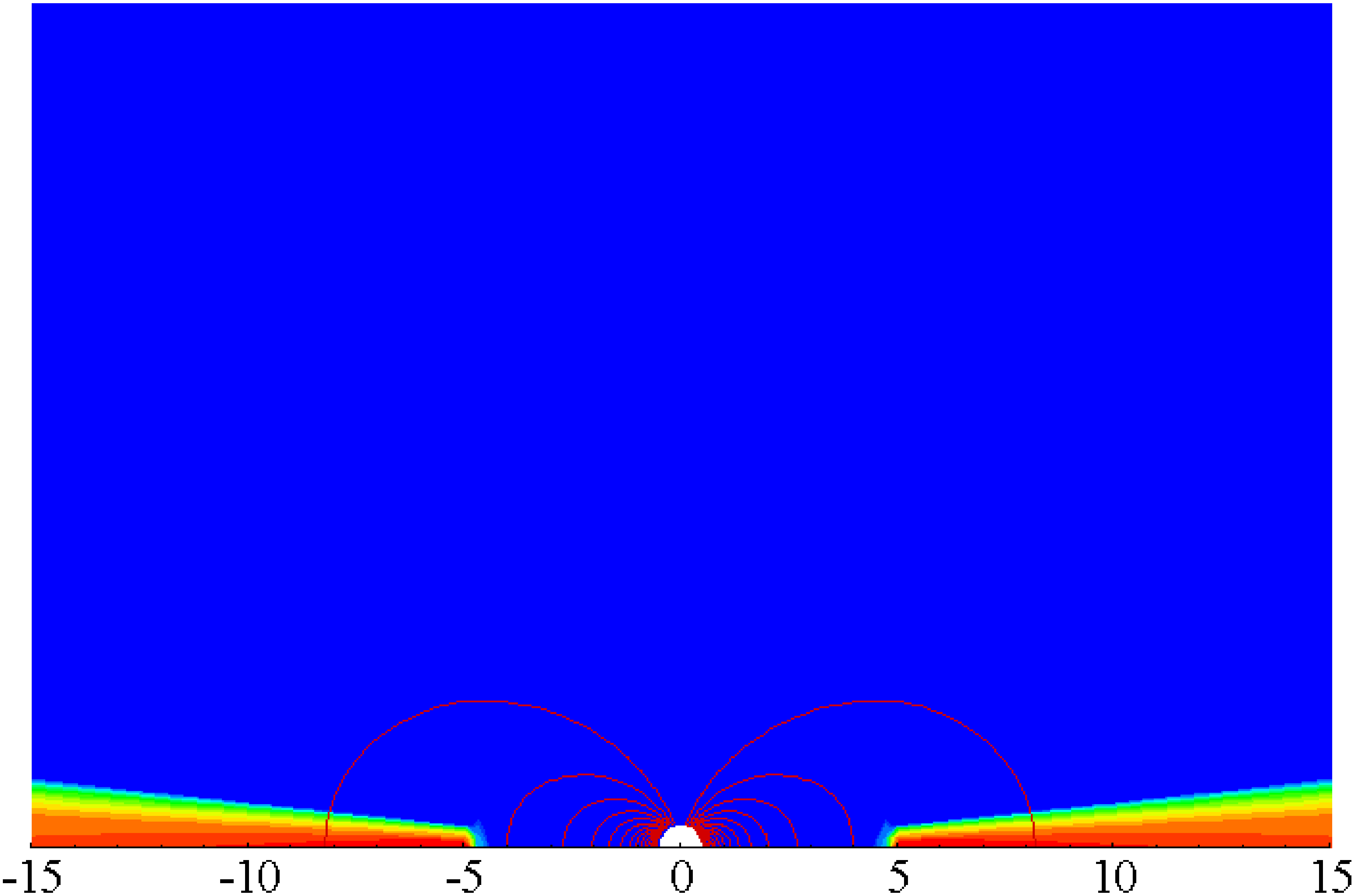
“Strong” propeller:

Investigation of propeller at different parameters: μ, Ω, αvis, αdif

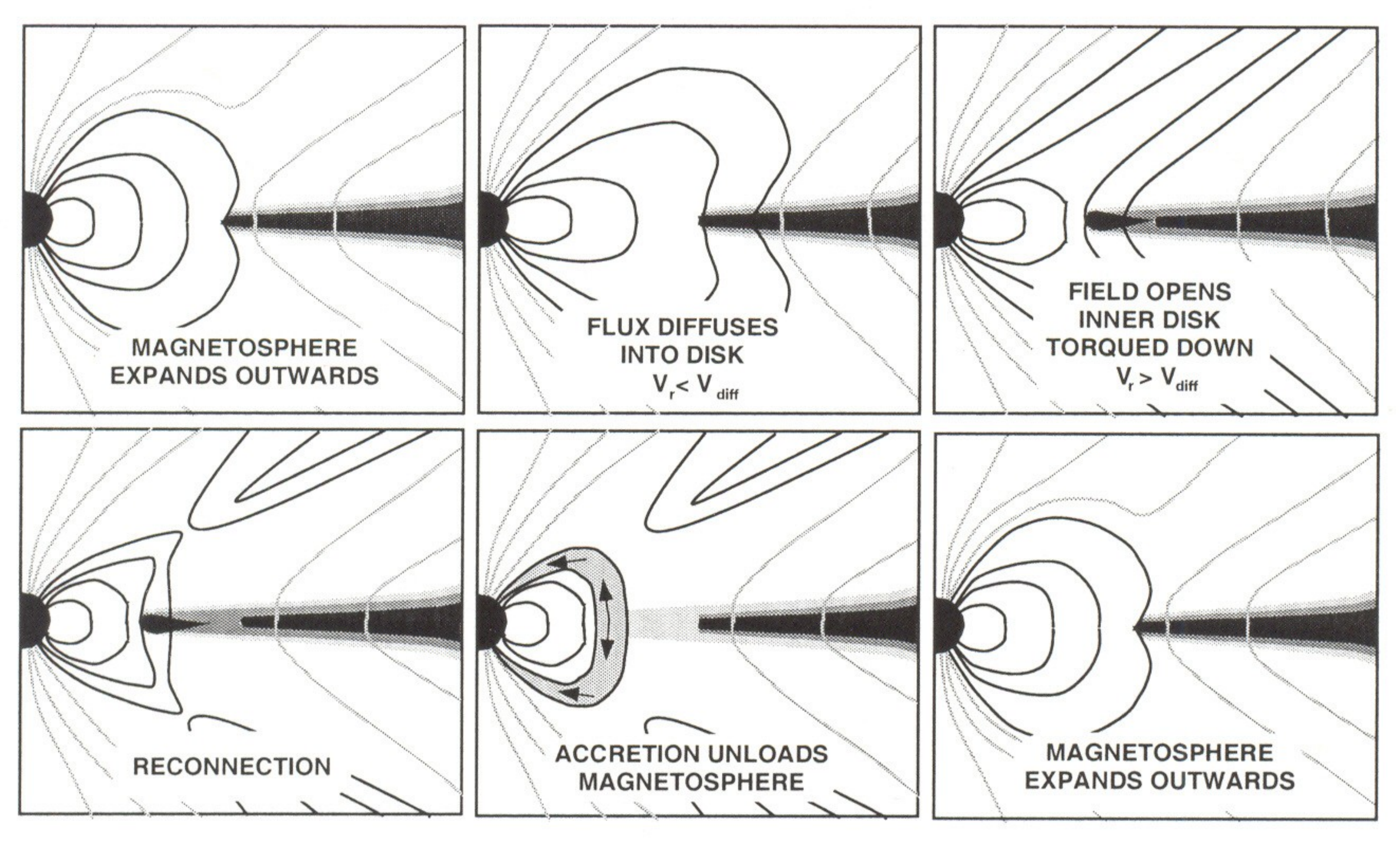
vis dif

α >0.1, α >0.03

OUTFLOWS !

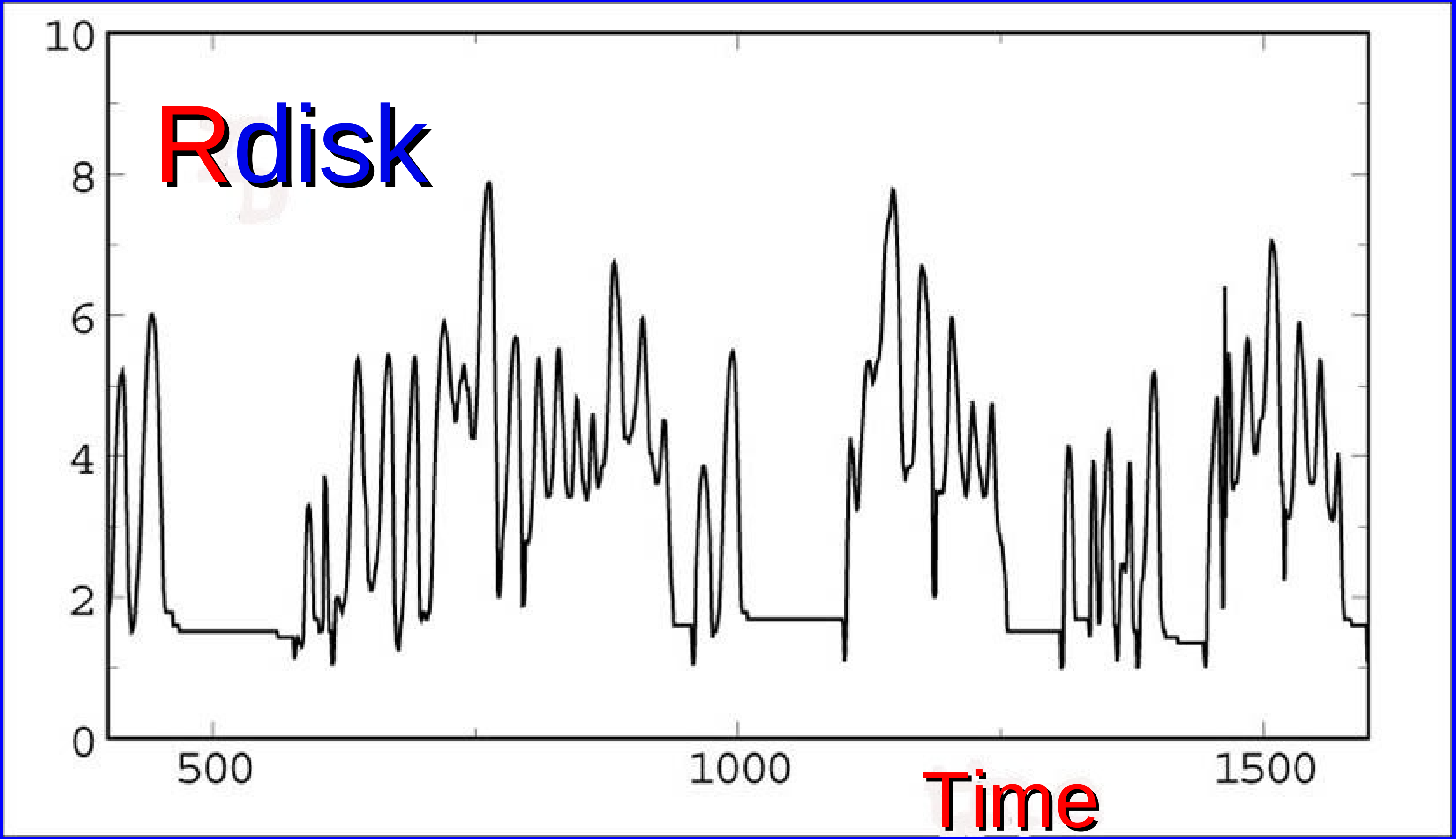

-15
-10
-5
0
5
10
15

Cycle of the Disk-Magnetosphere Interaction



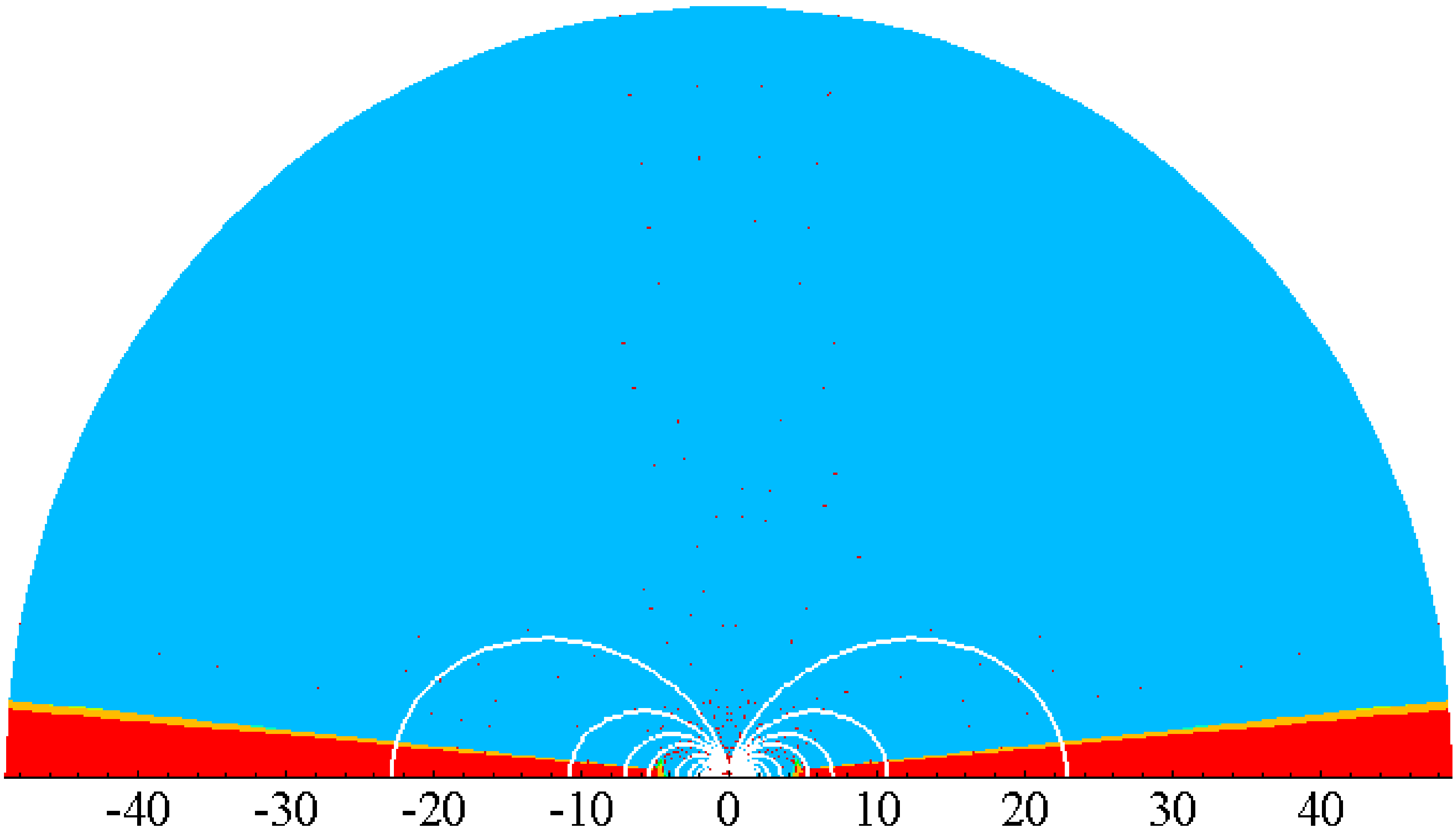
Goodson & Winglee (1999)

Variation of the Disk Radius with Time

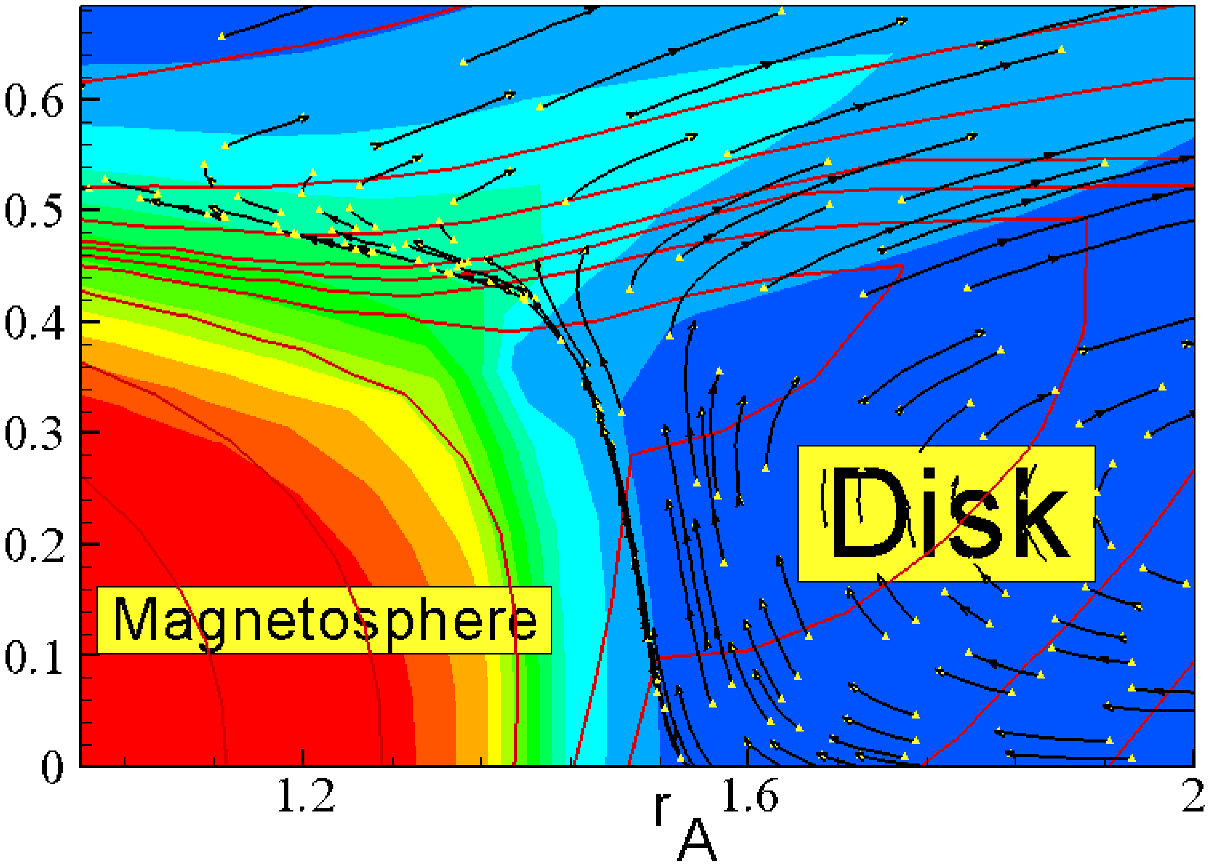


$$R_{disk} = r_m \quad (\rho v^2/2 = B^2/8\pi)$$

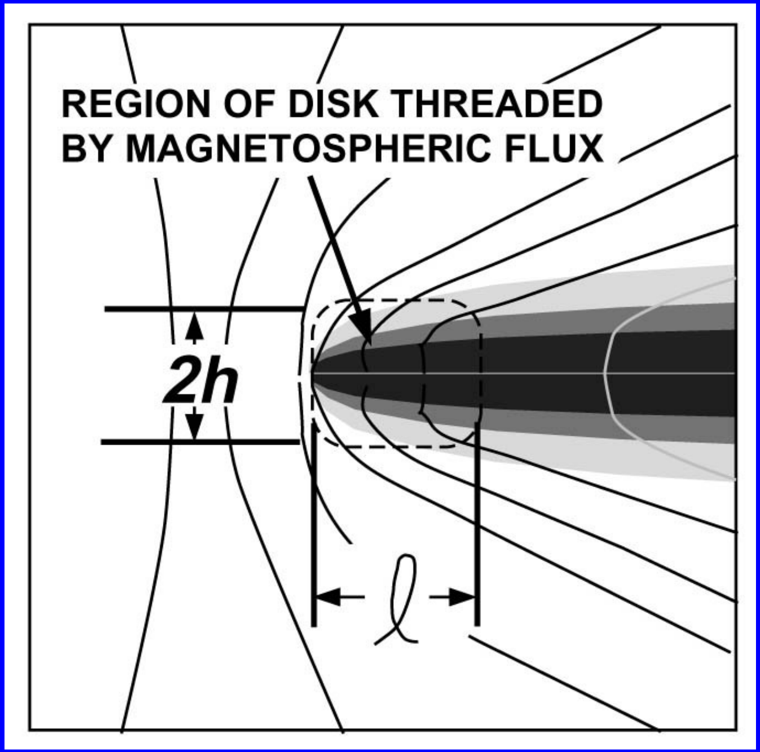
see also Spruit & Taam 1993


-40
-30
-20
-10
0
10
20
30
40

Angular velocity



Mixing of the Disk Matter to the Magnetosphere

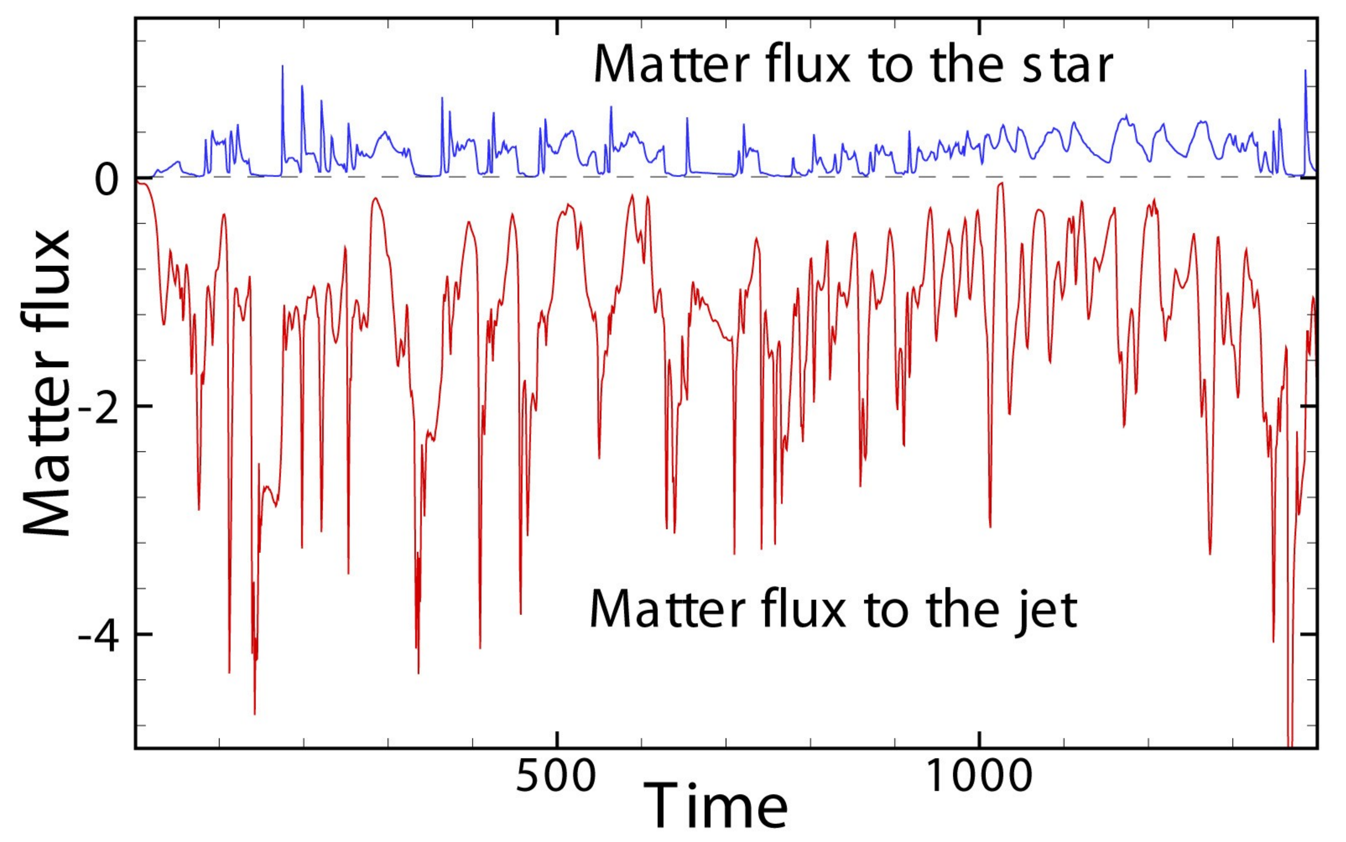


Goodson & Winglee (1999)

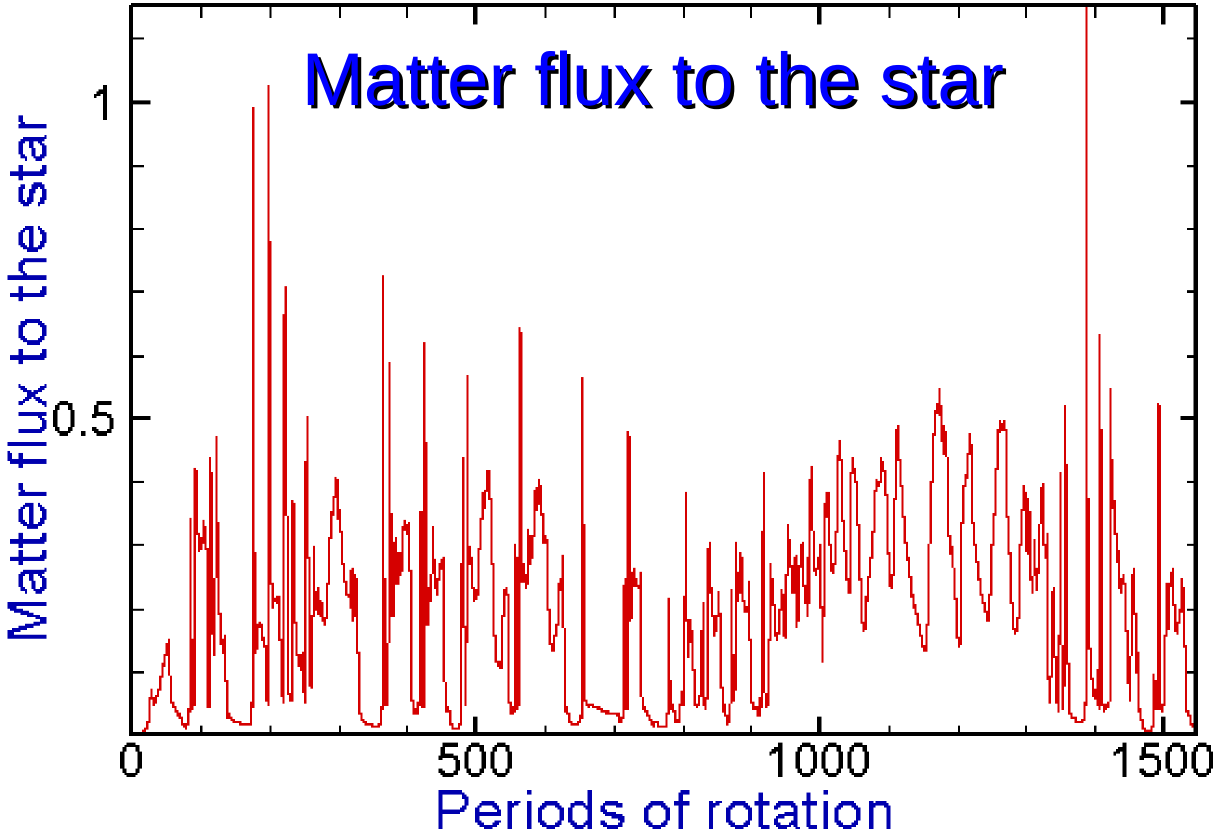
$$\text{timescale} = \frac{\ell^2}{\eta_m} \sim 1s \ ,$$

$$\text{for } r_m = 40\text{km} \ , \eta_m = 0.05 c_s h \ , \ell \sim r_m \ .$$

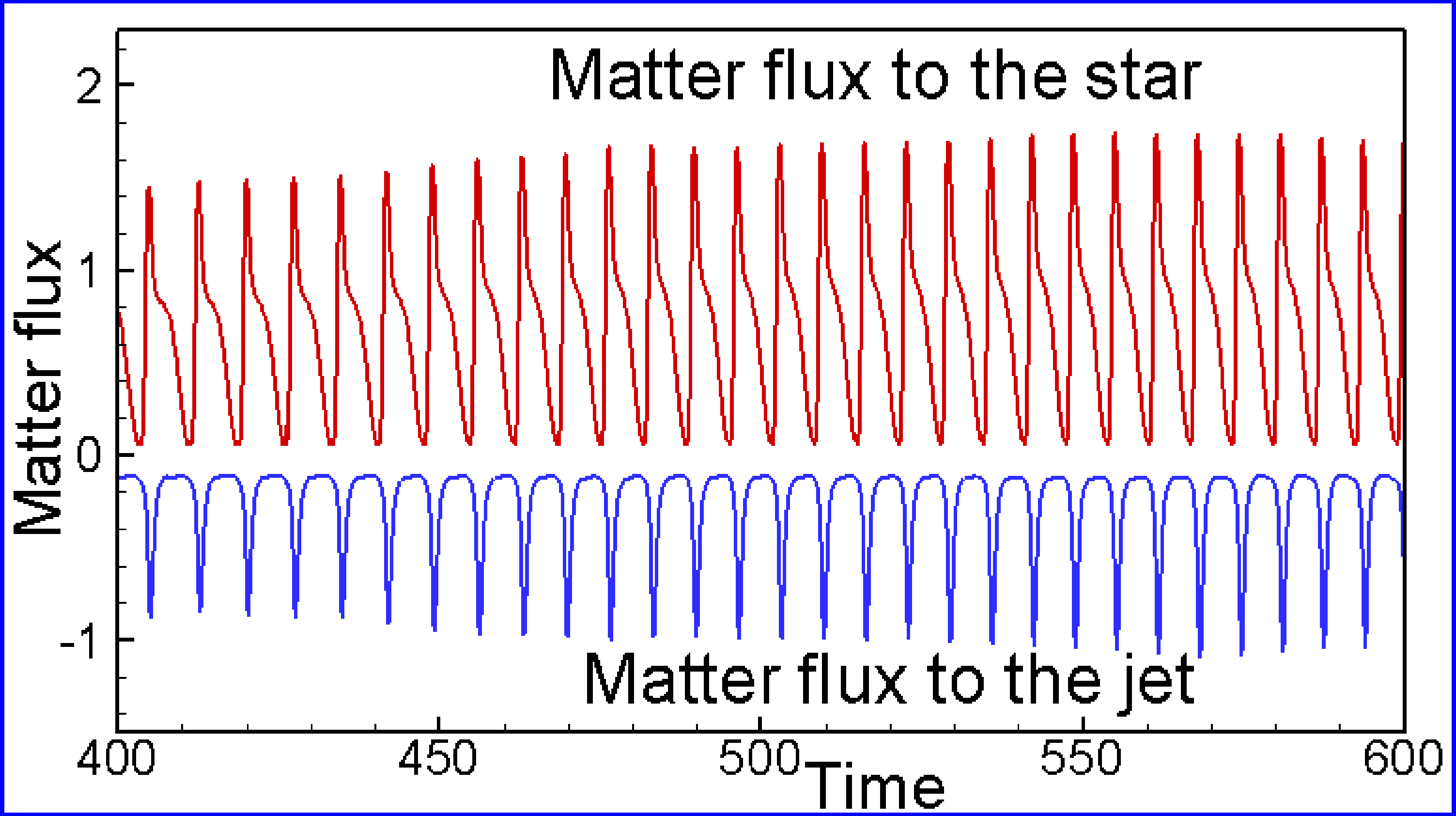
Bursting oscillations



Quasi-periodic oscillations

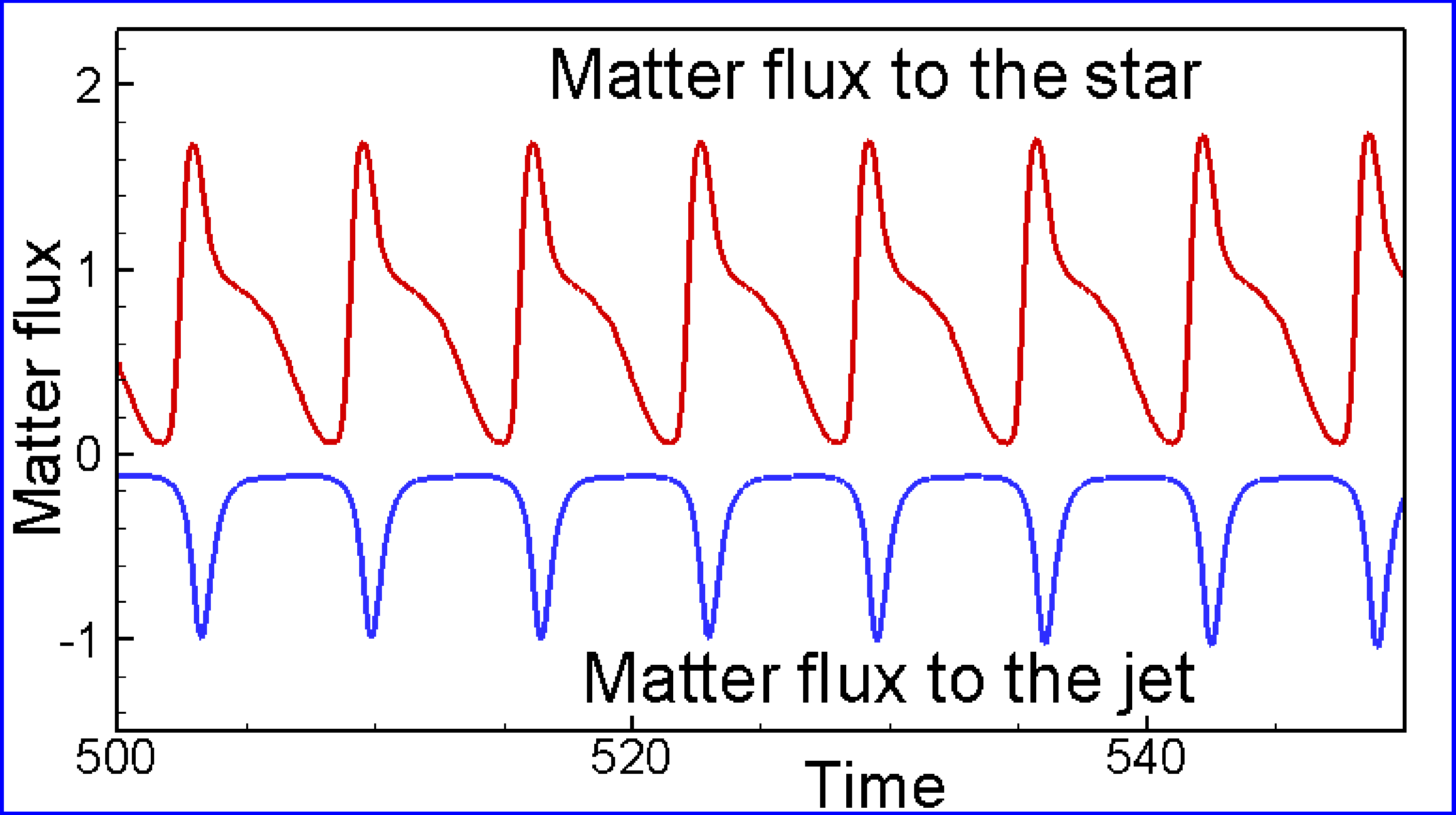


Larger viscosity case:



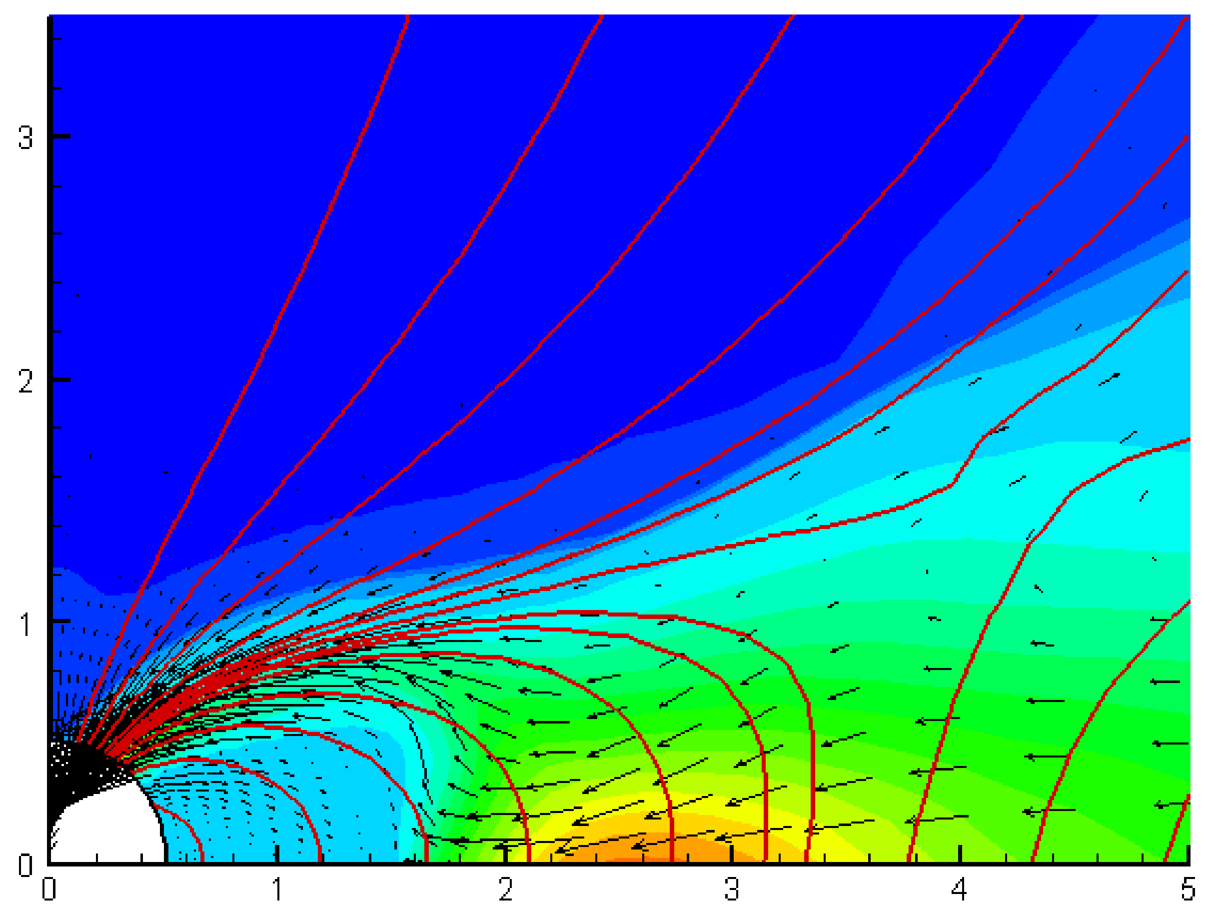
$\alpha_{vis}=0.6$ $\alpha_{dif}=0.2$

Larger viscosity case:

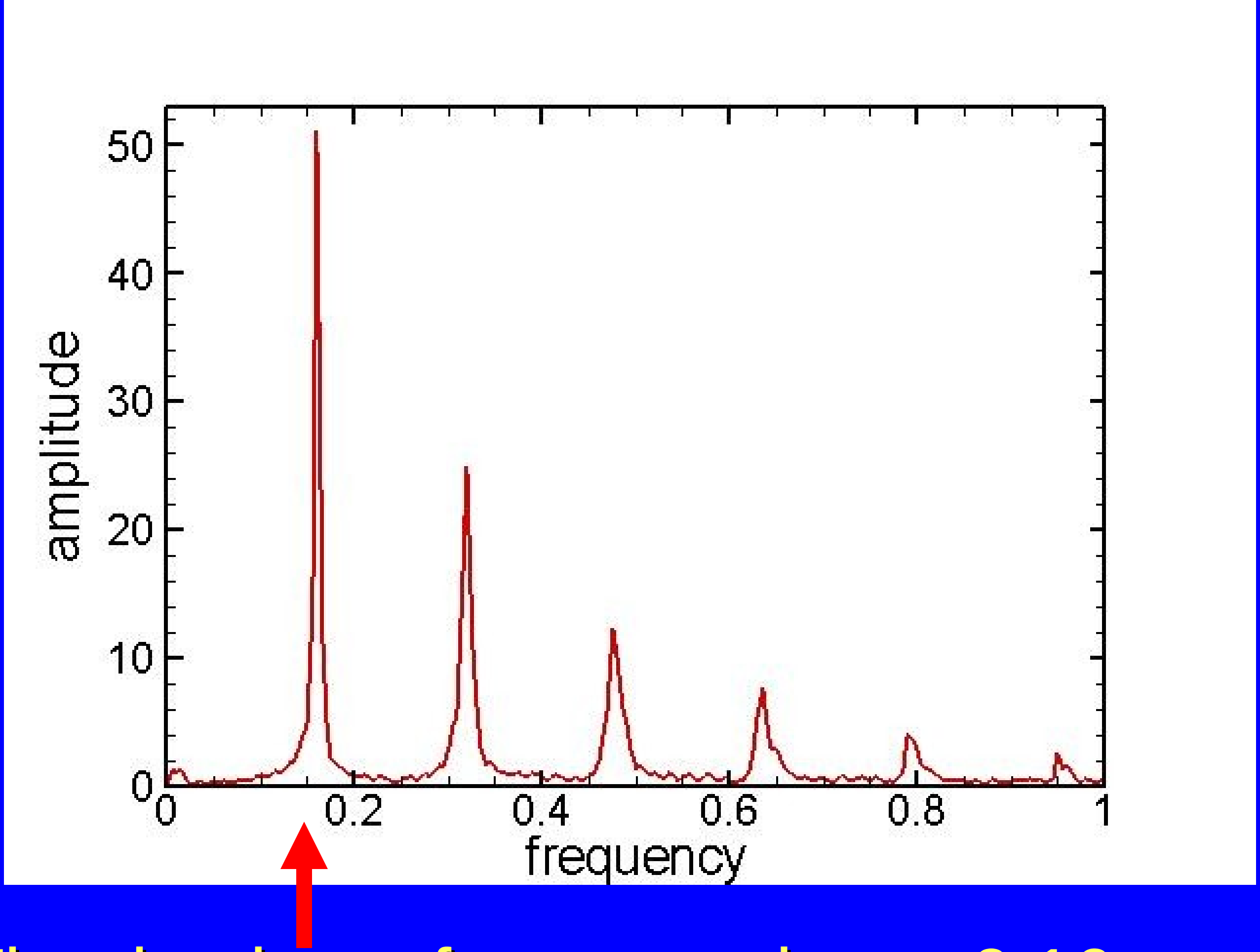


Accretion and outflows simultaneously

Well-tuned Oscillations:



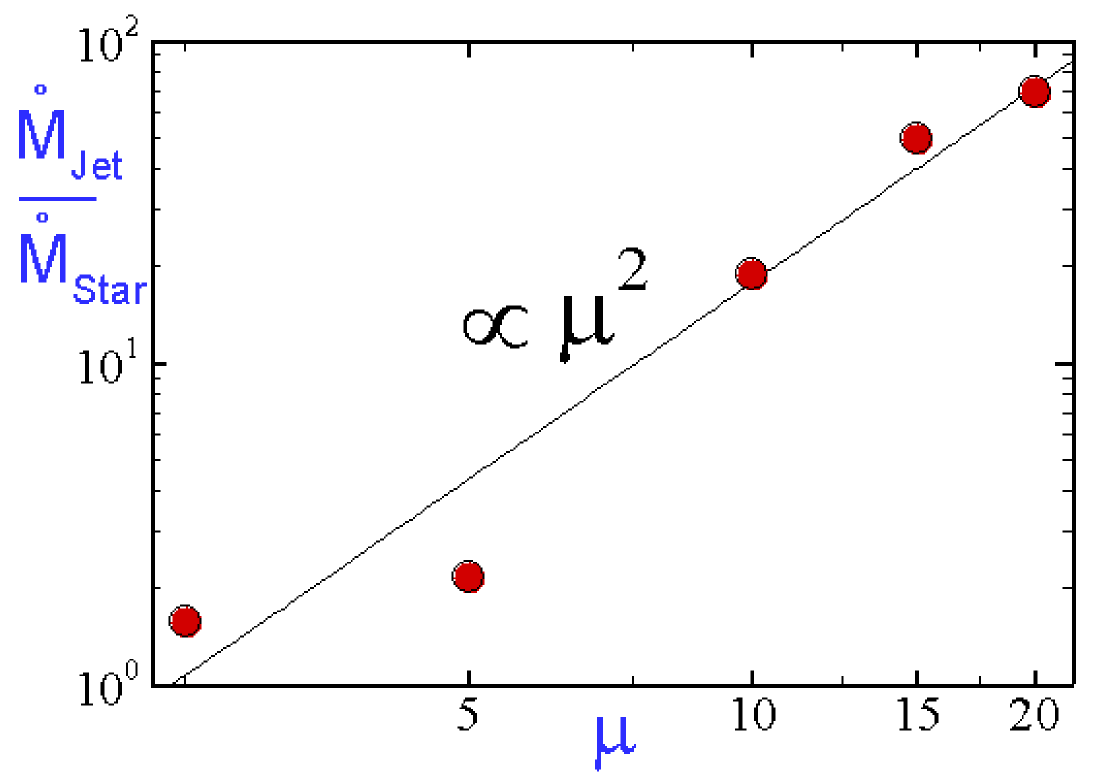
Fourier Analysis:



The dominant frequency is $\nu = 0.16$

P = 6.2 rotations at r=1

Mass Ejection / Accretion



Dependence on magnetic moment

Hartman et al. (2008) SAX J1808

Pulsar wind:

$$N_{\mathrm{dipole}} = -\mu^2(2\pi\nu/c)^3(1+\sin^2\alpha),$$

Spitkovsky (2006)

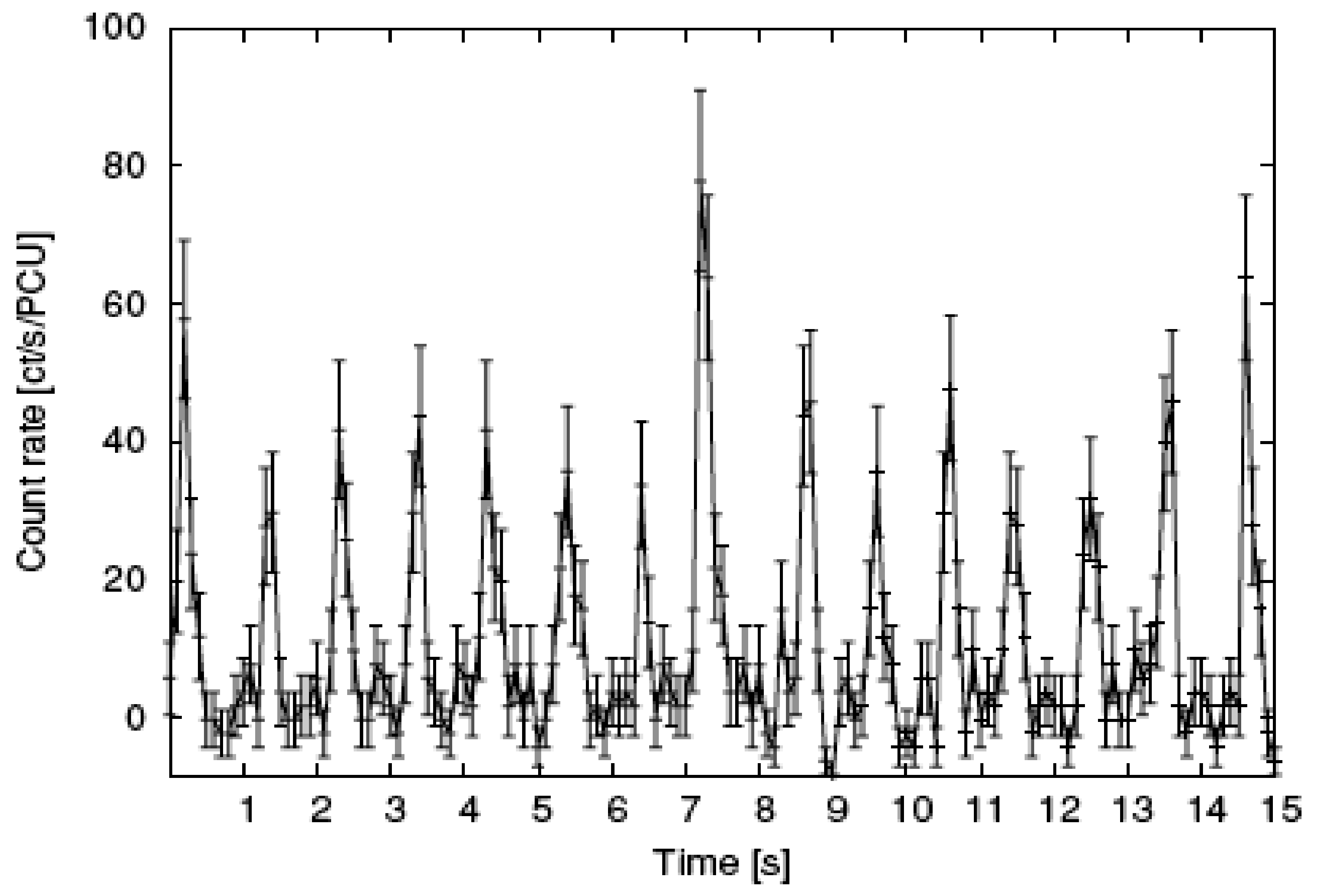
=> B ~10^8 G

Propeller outflow:

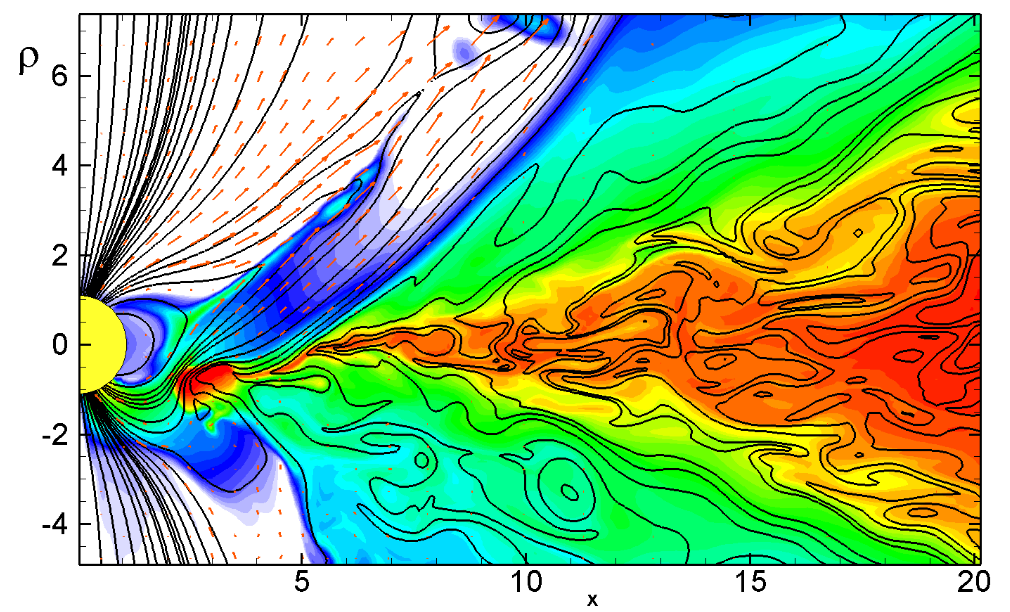
$$\begin{aligned} N_{\mathrm{prop}} &= -n\dot{M}_{\mathrm{ej}}(GMr_0)^{1/2}, \\ &= -n(r_0/r_{\mathrm{co}})^{1/2}\dot{M}_{\mathrm{ej}}(GMr_{\mathrm{co}})^{1/2}, \end{aligned} \qquad (15)$$

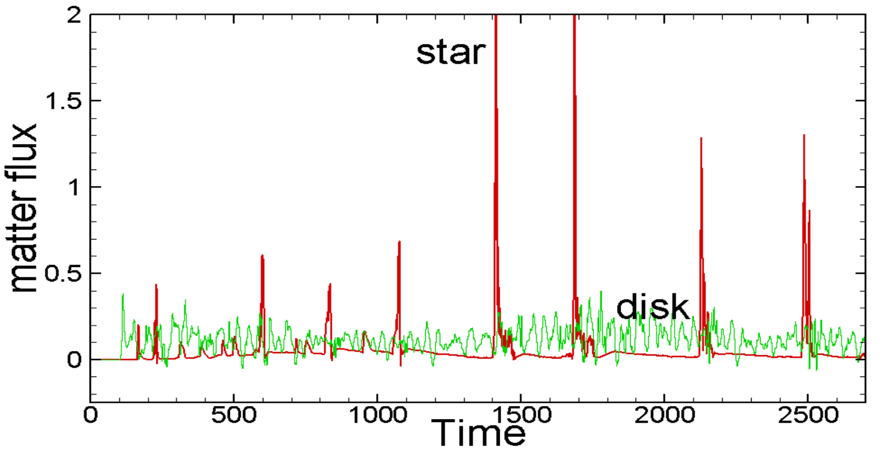
$$\begin{aligned} \dot{M}_{\mathrm{ej}} < &-2.3\times10^{-12}n^{-1}(r_0/r_{\mathrm{co}})^{-1/2} \\ &\times \frac{I}{10^{45}\ \mathrm{g\ cm^2}}\left(\frac{M}{1.4\ M_\odot}\right)^{-2/3}\left(\frac{\nu}{401\ \mathrm{Hz}}\right)^{1/3} \\ &\times \frac{-\dot{\nu}}{5.6\times10^{-16}\ \mathrm{Hz\ s^{-1}}}\ M_\odot\ \mathrm{yr^{-1}}. \end{aligned} \qquad (16)$$

Patruno et al. 2009 SAX J1808



Propeller Regime – episodic accretion and outflows due to MRI accretion to rotating star with dipole field





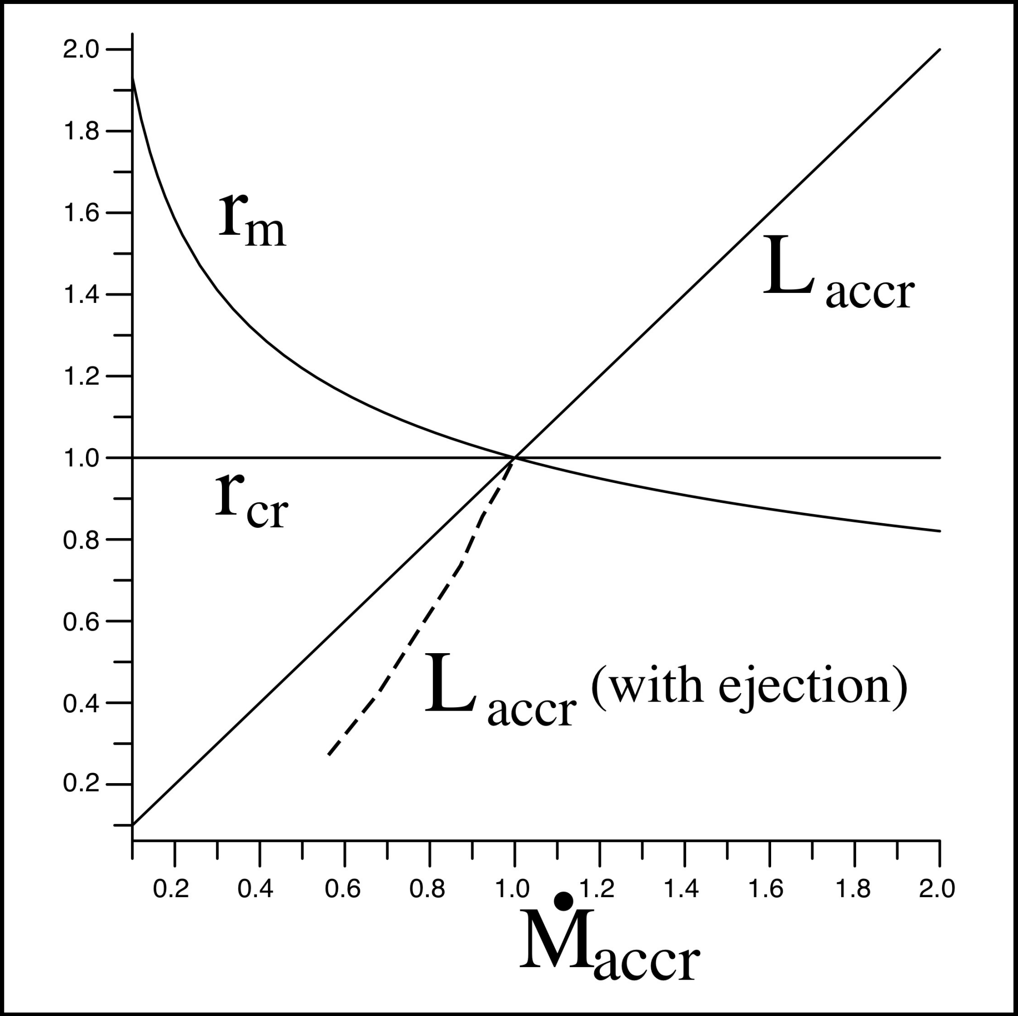
Outbursts every 300 ms

Similar to Spruit & Taam 1993
D'Angelo & Spruit 2011

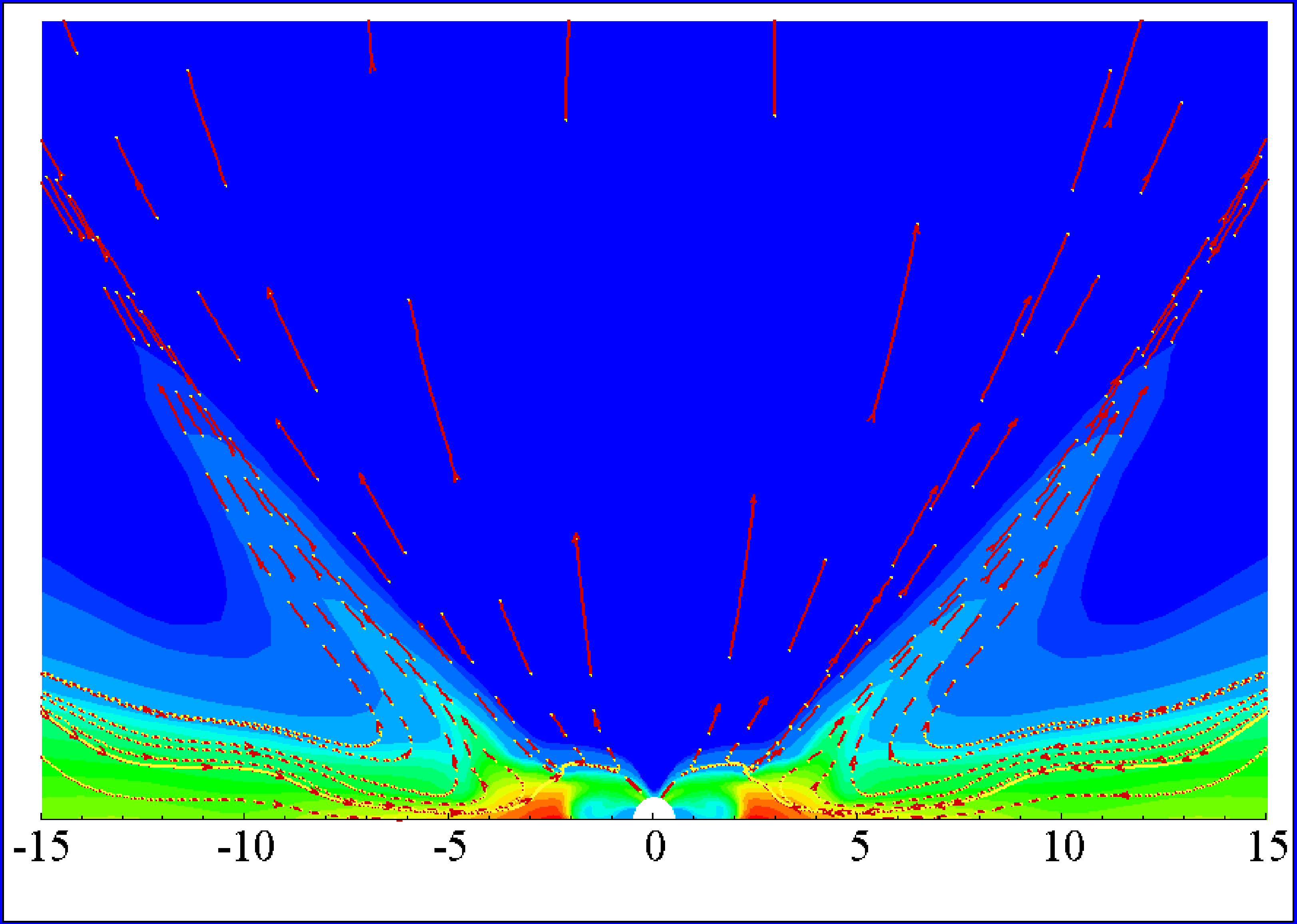
Ustyugova et al. 1011, in prep

Conclusions

- There are two types of propellers:
  - ”strong”: oscillations + outflows
  - “weak”: only oscillations, weak or no outflows
- “Weak” propellers are observed for a wide set of parameters
- “Strong” propellers appear at larger viscosity and diffusivity
- Matter flows in conical outflow with super-escape velocities, magnetic energy and some matter flows to a collimated, magnetically dominated jet


2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
r_m
r_{cr}
L_{accr}
L_{accr} (with ejection)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
$\dot{M}_{accr}$

Conical outflows:



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Balbus 2003, Hawley & Stone – simulations

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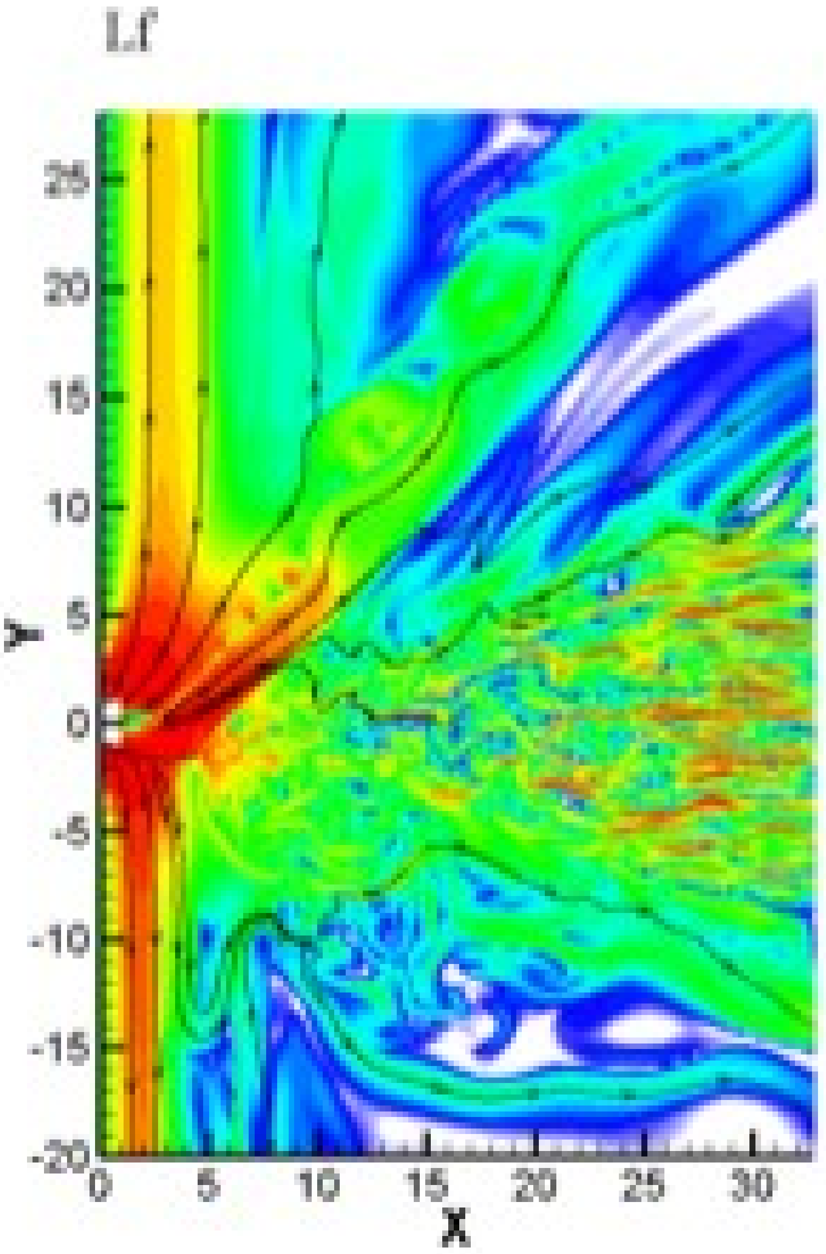
αvis=0.01-1 αdif=0.01-1


Lf
25
20
15
10
5
0
-5
-10
-15
-20
Y
0
5
10
15
20
25
30
X