Theory of magnetar activity

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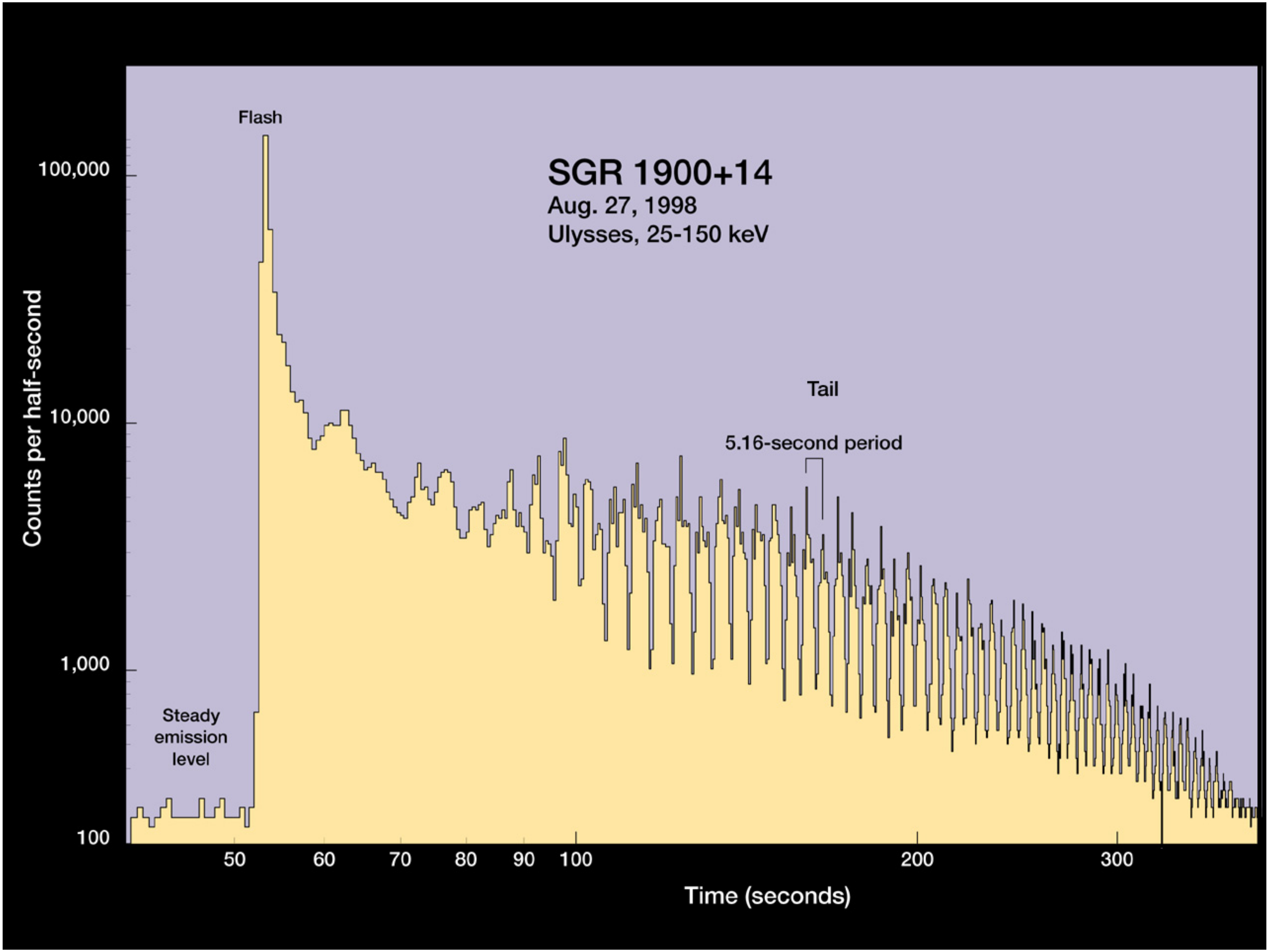
1. Observed coronal activity
2. ~~Crustal stresses and deformations~~
3. Electrodynamics of active magnetospheres
4. Outbursts
5. Spindown
6. Electron-positron plasma
7. Turbulence and low-frequency emission
8. Nonthermal X-ray emission

Luminosities from neutron stars are powered by:

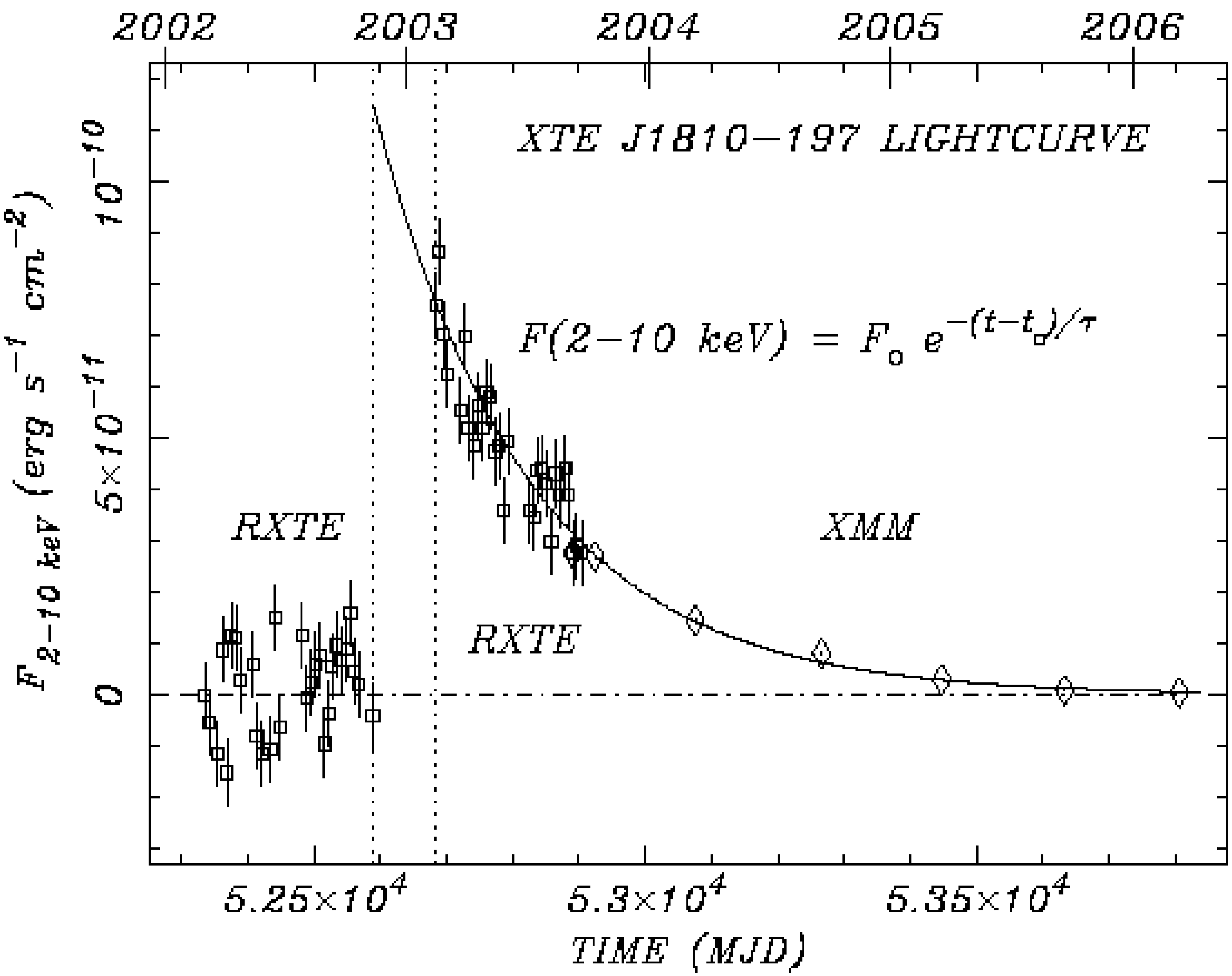
- Stored heat
- Accretion
- Rotation
- **Magnetic field (“magnetars”)**

(Duncan, Thompson 1992
Paczynski 1992)



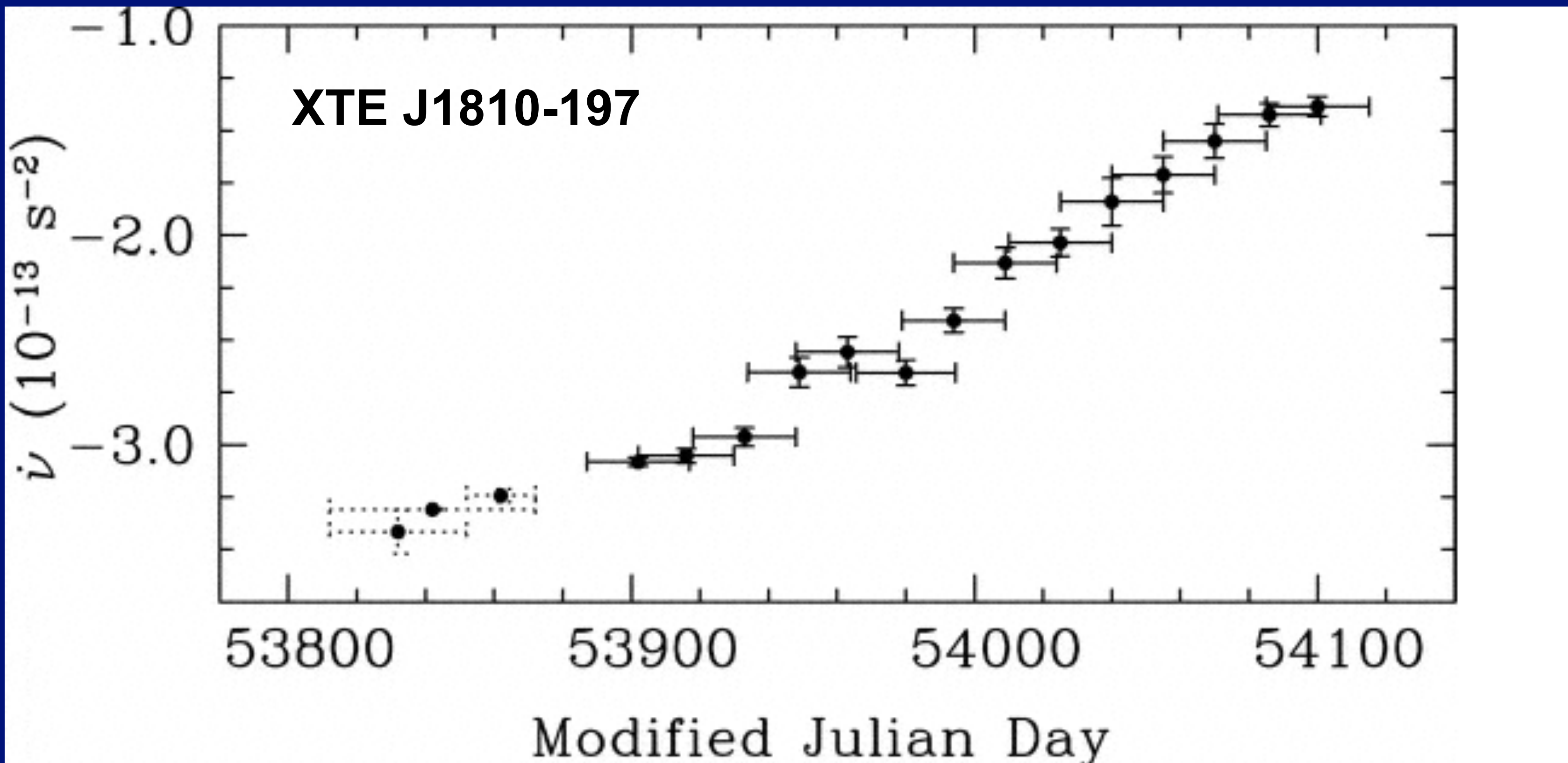
SGR 1900+14
Aug. 27, 1998
Ulysses, 25-150 keV
Flash
Tail
5.16-second period
Steady emission level
Counts per half-second
100,000
10,000
1,000
100
50
60
70
80
90
100
200
300
Time (seconds)

XTE J1810-197



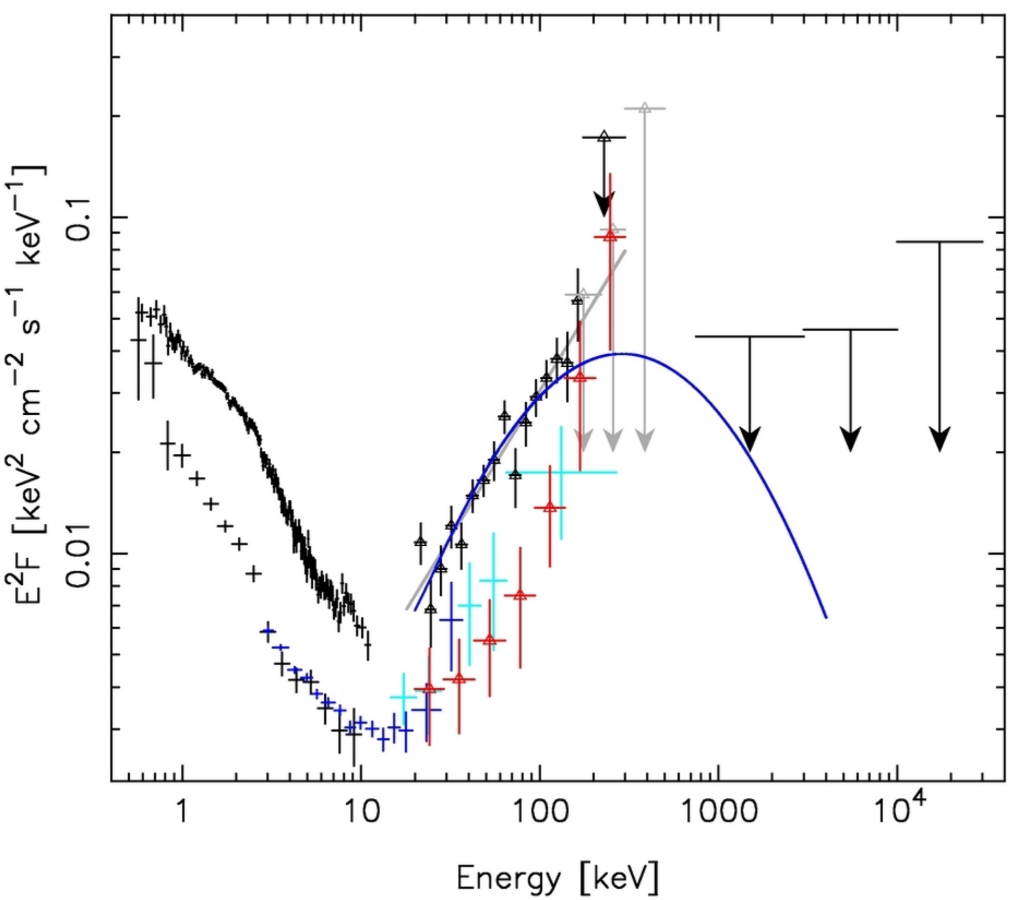
Gotthelf, Halpern (2007)

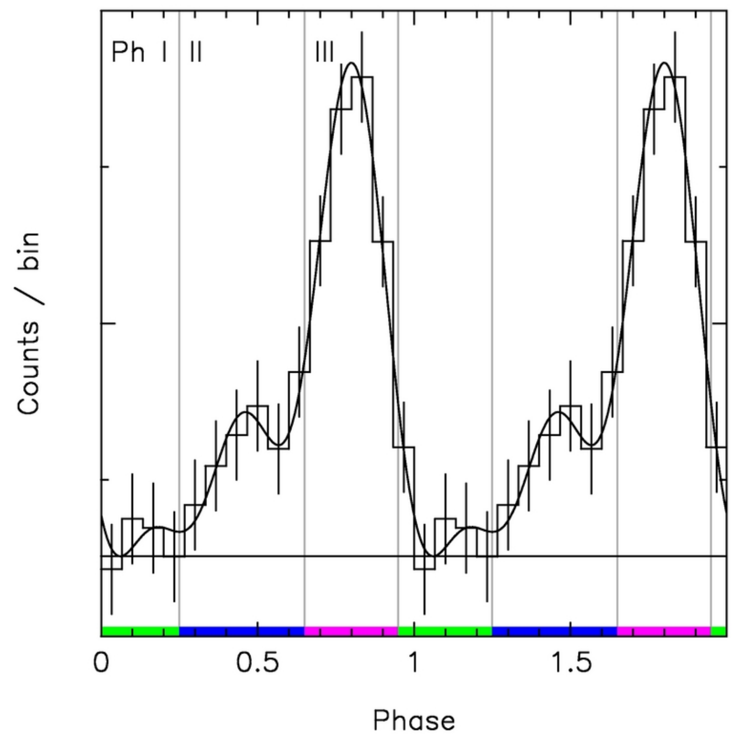
Dynamic spindown torque



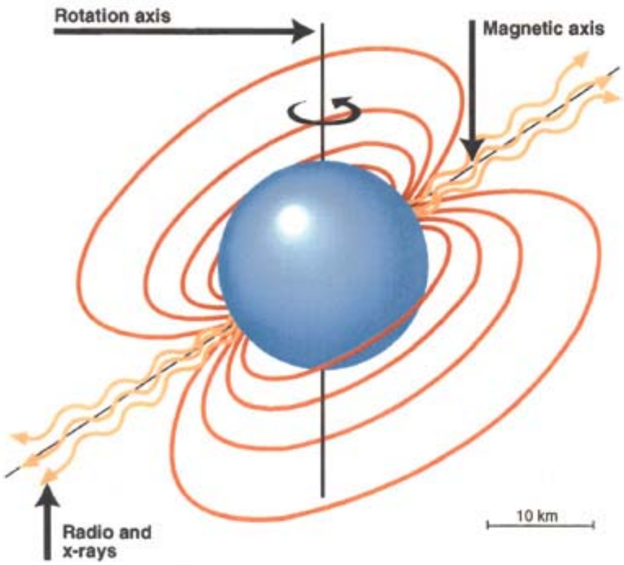
Camilo et al. (2007)

AXP 1RXS J170849-400910





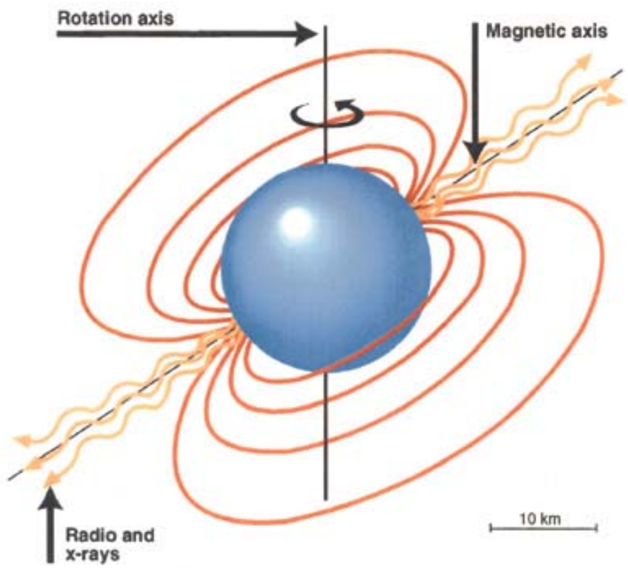
Den Hartog et al. (2008)



Ordinary pulsars: twisted **open** field lines

magnetospheric power $L = I\Phi < L_{\mathrm{SD}}$

current $I \sim \dfrac{c\ \mu}{R_{\mathrm{LC}}^2}$, voltage $\Phi \sim 10^{12}\,V$



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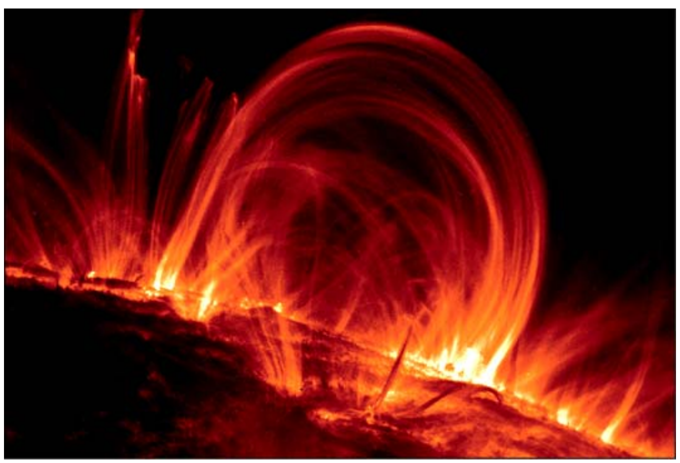

Magnetars: twisted **closed** field lines (cf. the sun)

magnetospheric power $L = I\Phi >> L_{\mathrm{SD}}$

current $I \sim \frac{c\,\mu}{R_{\mathrm{NS}}^2}$, voltage $\Phi \sim 10^{9}\,V$

Twisted force-free configurations

(e.g. Low 1986;
Mikic, Linker 1994)

$$\nabla_{\mu} T^{\mu\nu} = 0$$

K. Parfrey

D. Vigano

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Global self-similar twists $\psi \sim 1$?

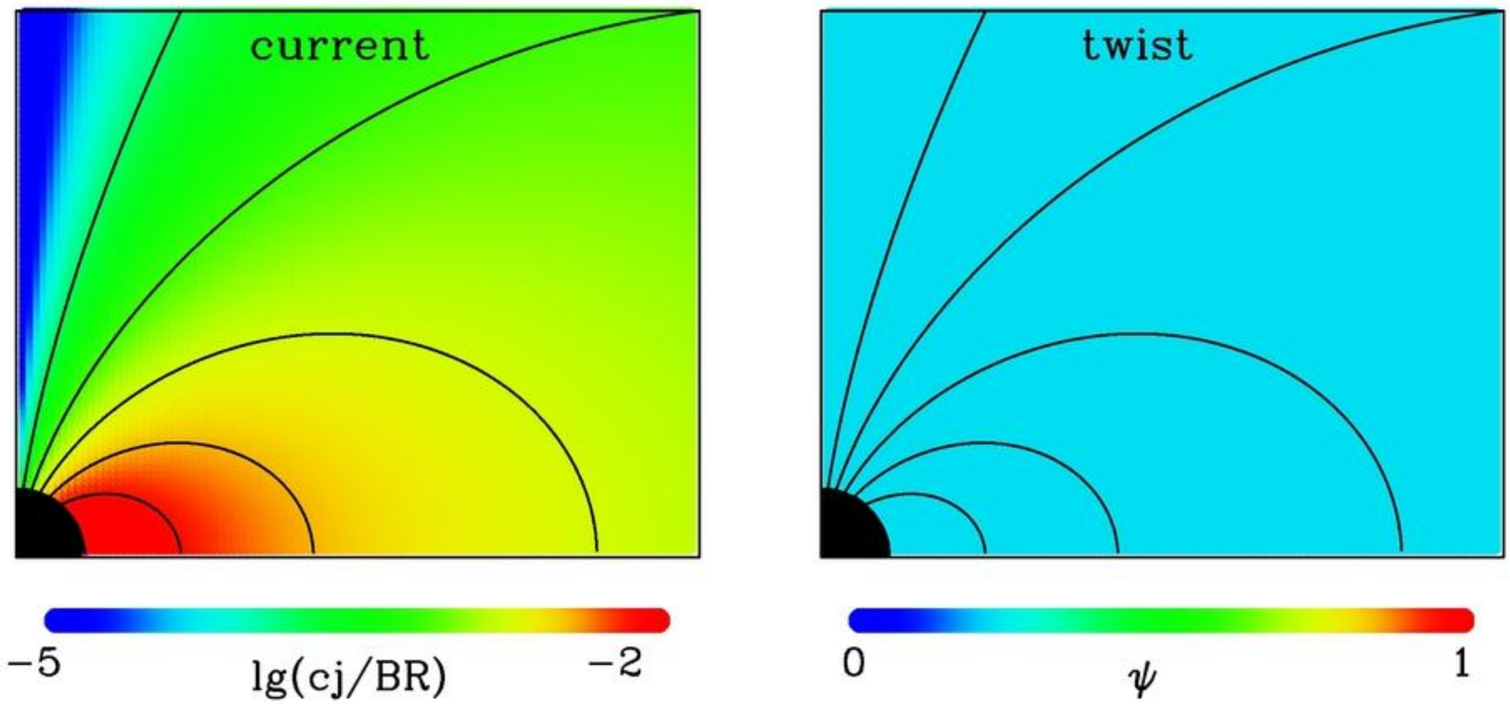
(Wolfson 1995;
Thompson et al. 2002;
Pavan et al. 2009)

-- luminosity too large

-- evolution too slow

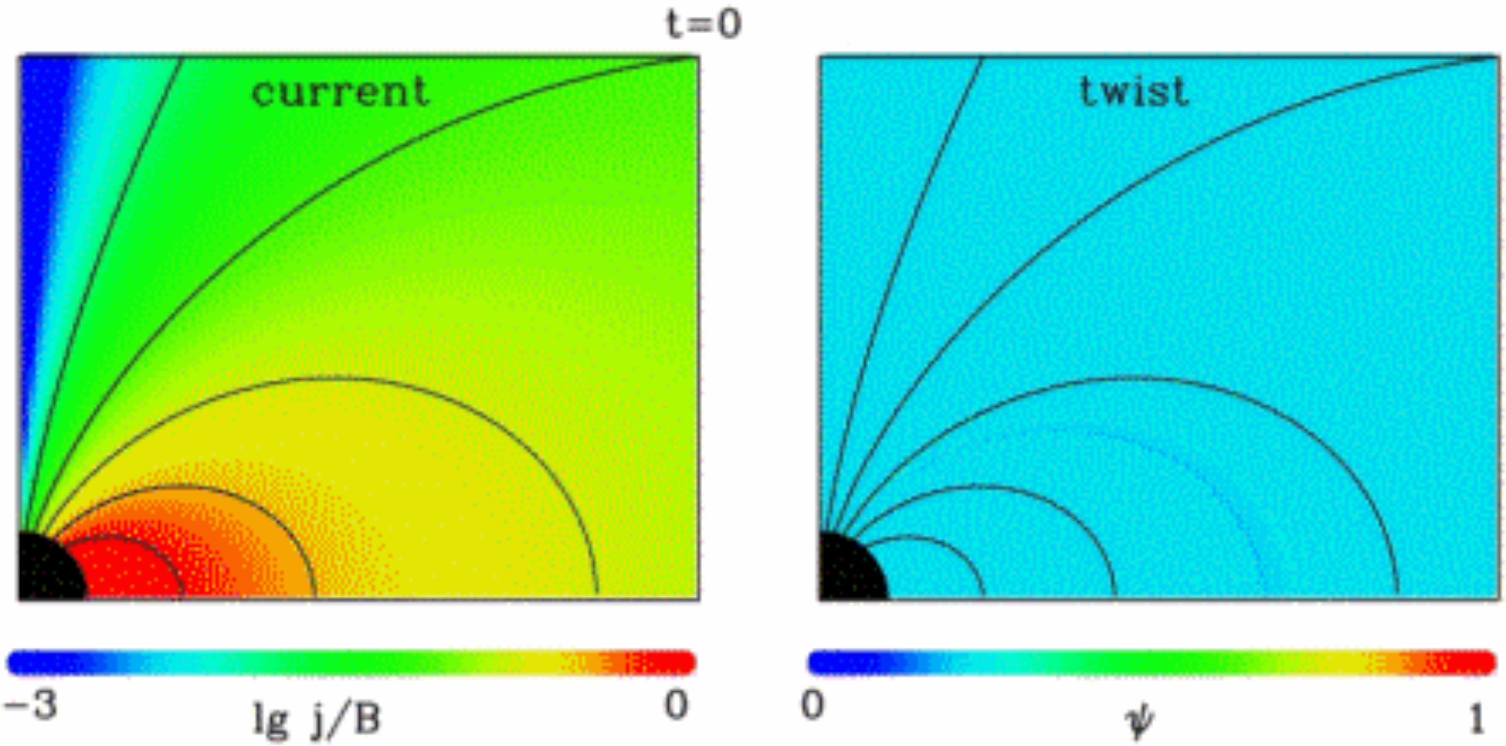
-- dynamic twist localization

Example: uniformly twisted dipole



$$\frac{\partial \psi}{\partial t} = c\frac{\partial \Phi}{\partial f}$$

(Beloborodov 2009)

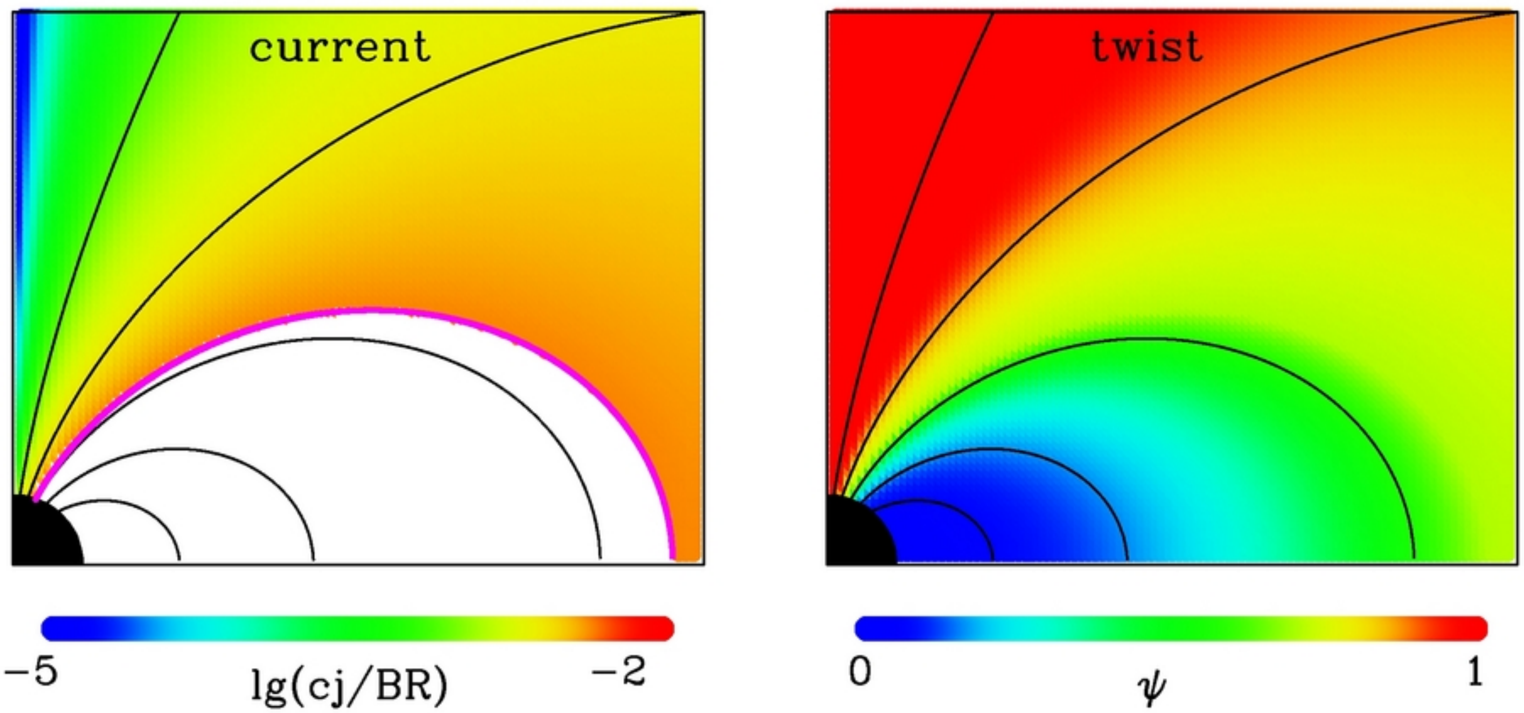


time units:

$$t_0 = \frac{\mu}{cR\bar{\bar{V}}}$$

$$\frac{\partial \psi}{\partial t} = c\frac{\partial \Phi}{\partial f}$$

(Beloborodov 2009)

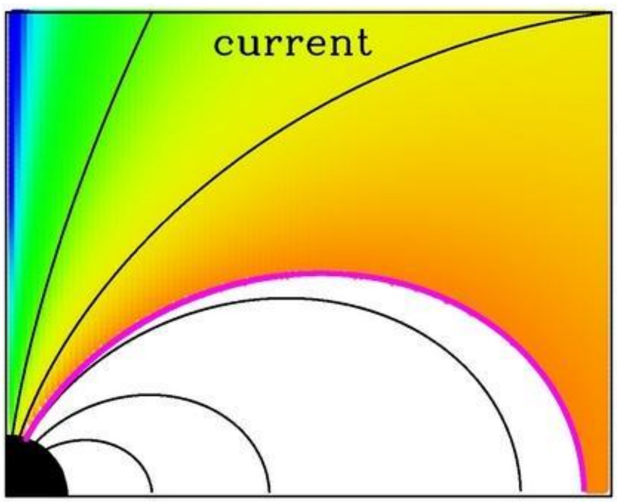


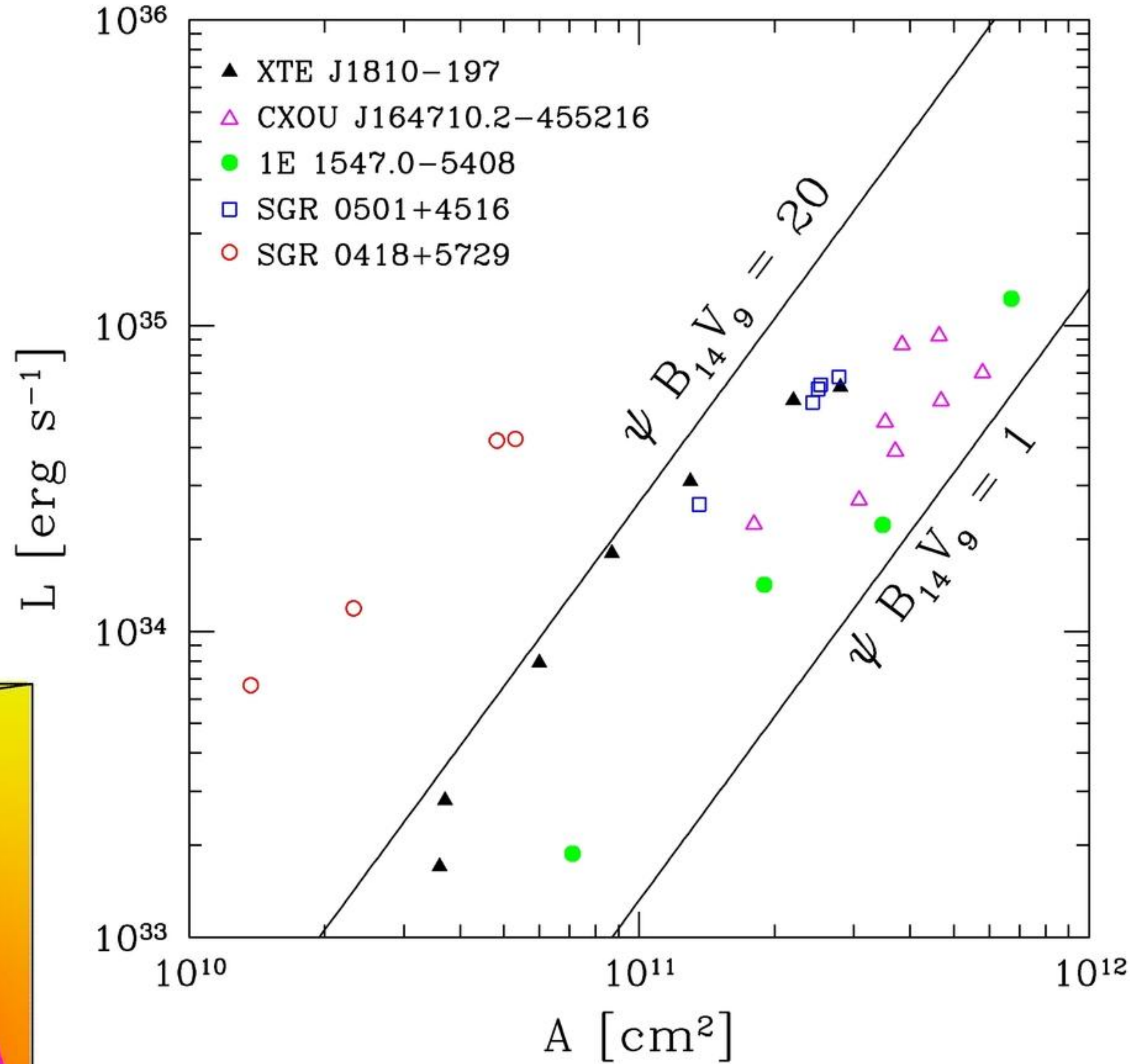
$$L = 1.3\times 10^{35}\ \Phi_9\ B_{14}\ \psi\ A_{12}^2 \quad [\text{erg s}^{-1}]$$

$$t_{\text{ev}} = 4\ \ \Phi_9^{-1}\ B_{14}\ \psi\ A_{12} \quad [\text{yr}]$$

(A – area of the j-bundle footprint)

Shrinking hot spots on transient magnetars:





Hot spot in XTE J1810-197

XTE J1810-197: *P = 5.54 s*

$B \sim 2 \times 10^{14}$ G

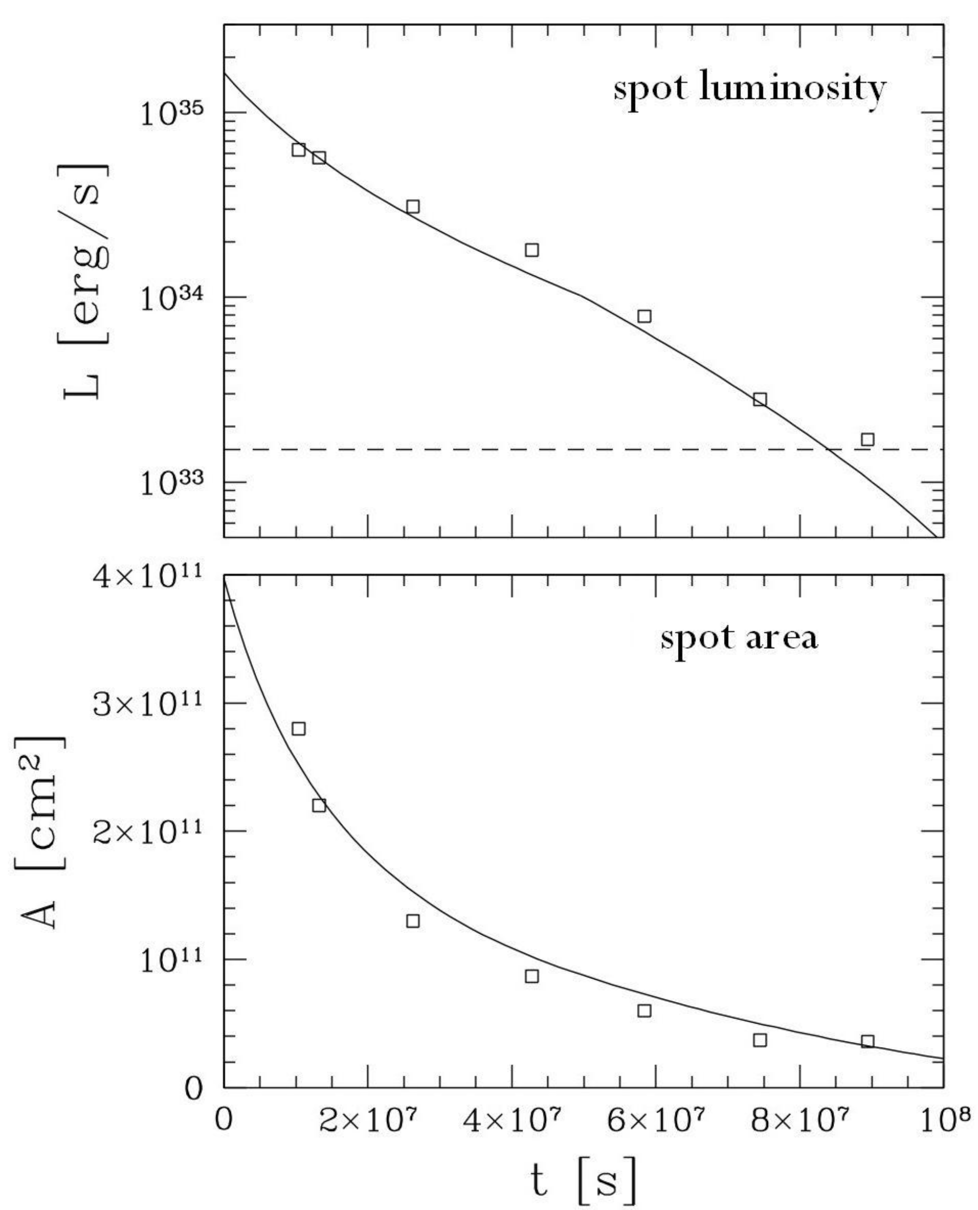
$L_{sd} \sim 3 \times 10^{32}$ erg/s

Starquake:

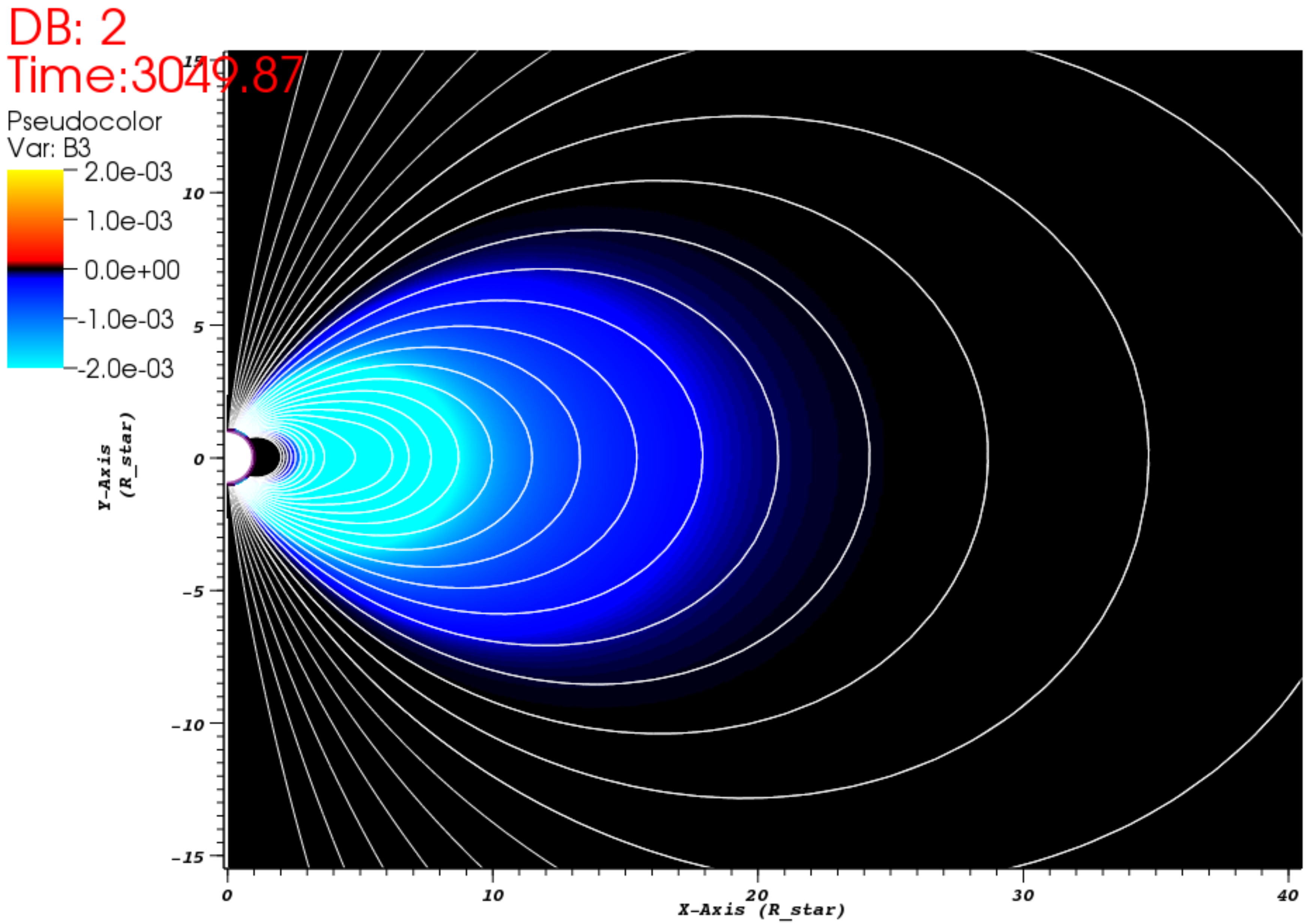
-- X-ray outburst (Ibrahim et al. 2004)

-- 3 year decay; shrinking hot spot
(Gotthelf, Halpern 2007;
Bernardini et al. 2009)

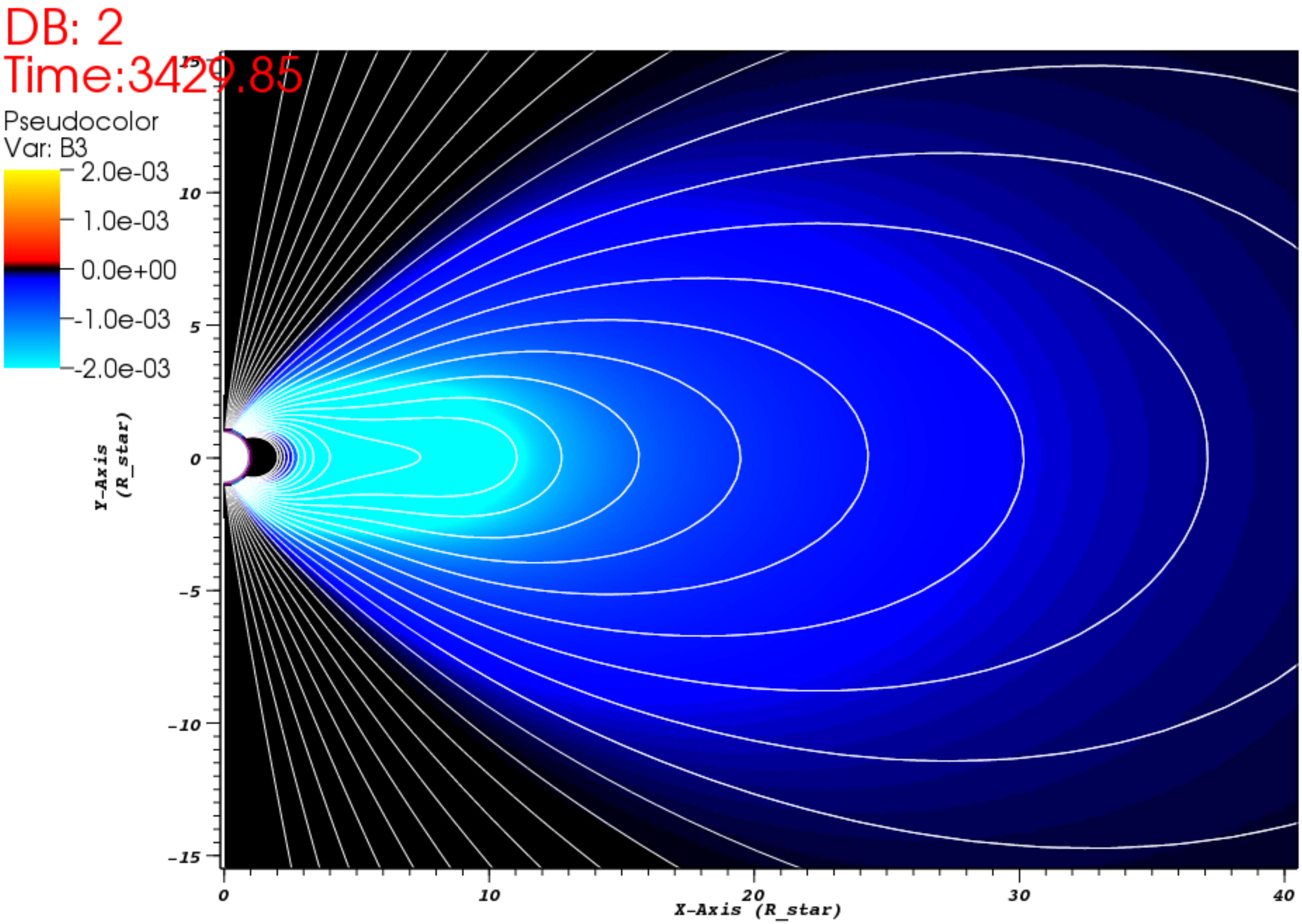
Voltage ~ 3 GeV



Outbursts from overtwisted j-bundle



Parfrey et al. (2011)



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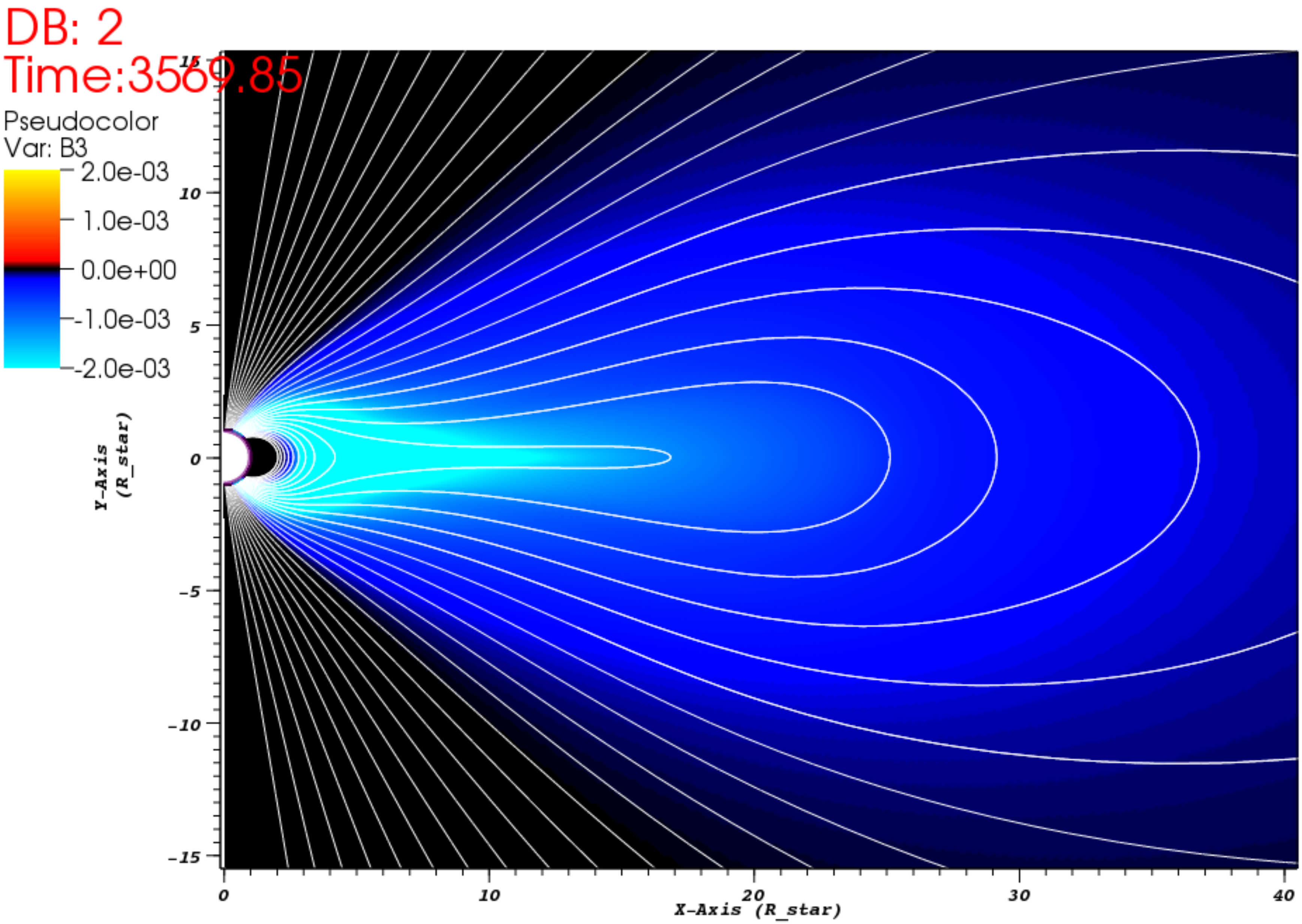

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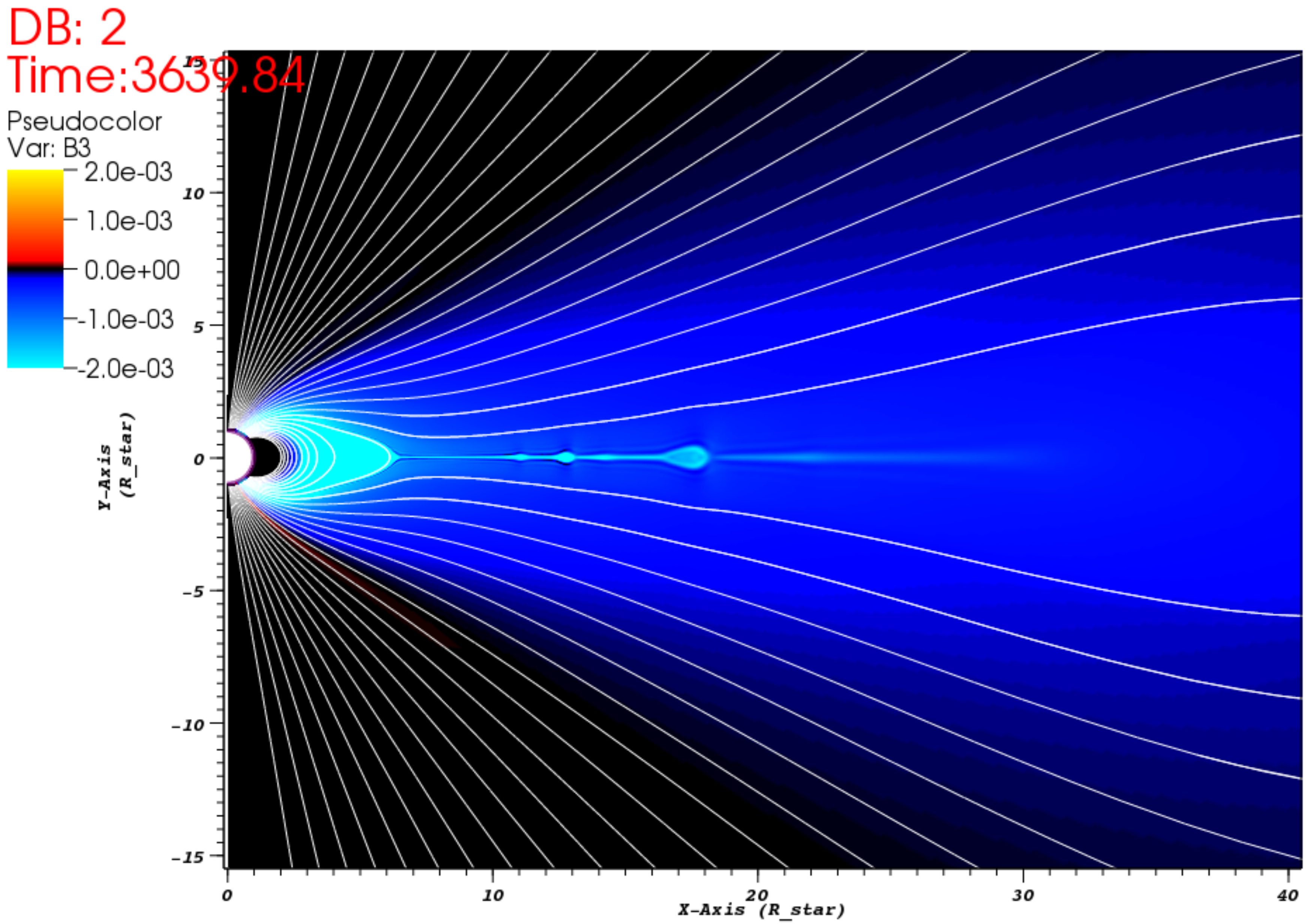

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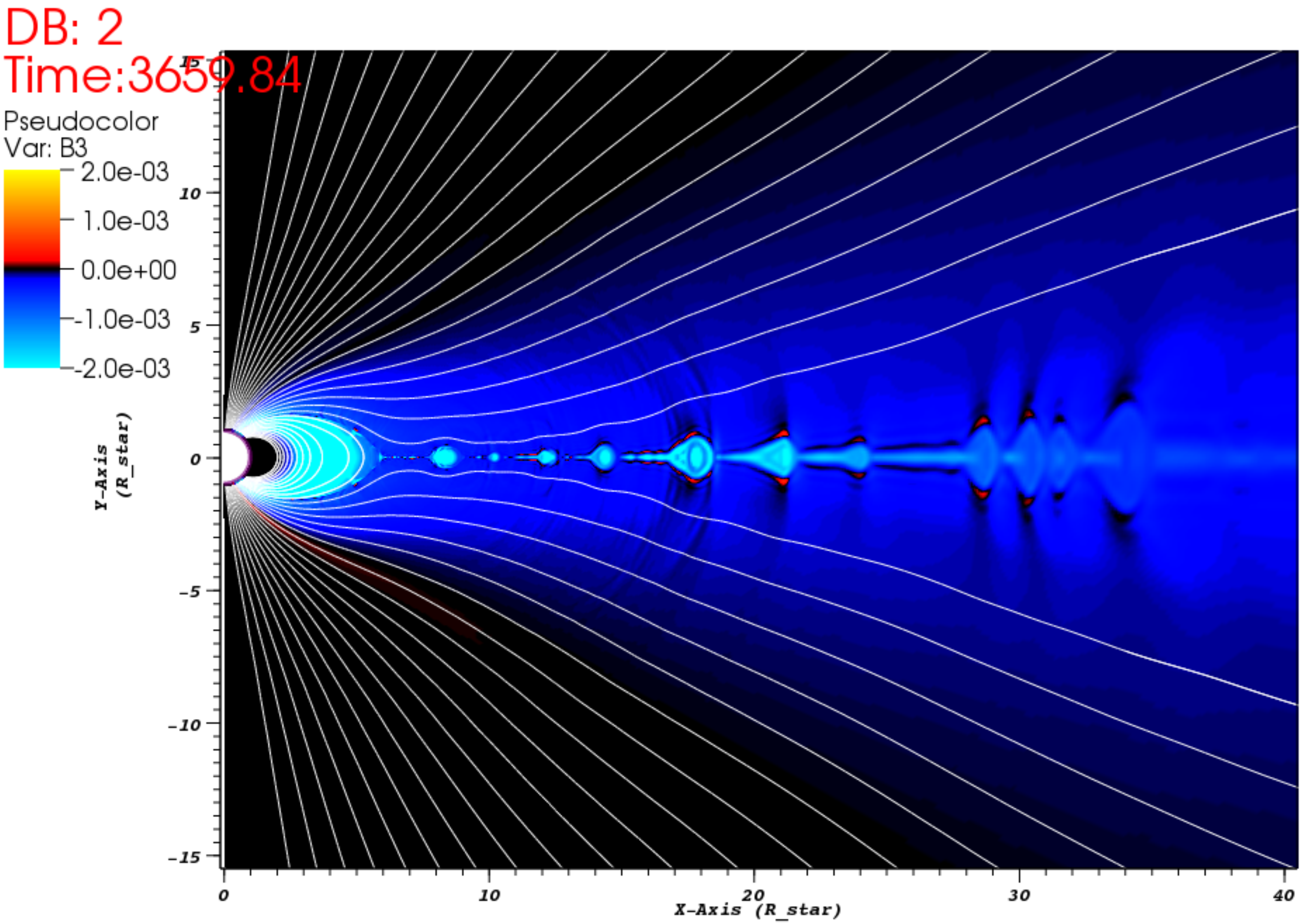

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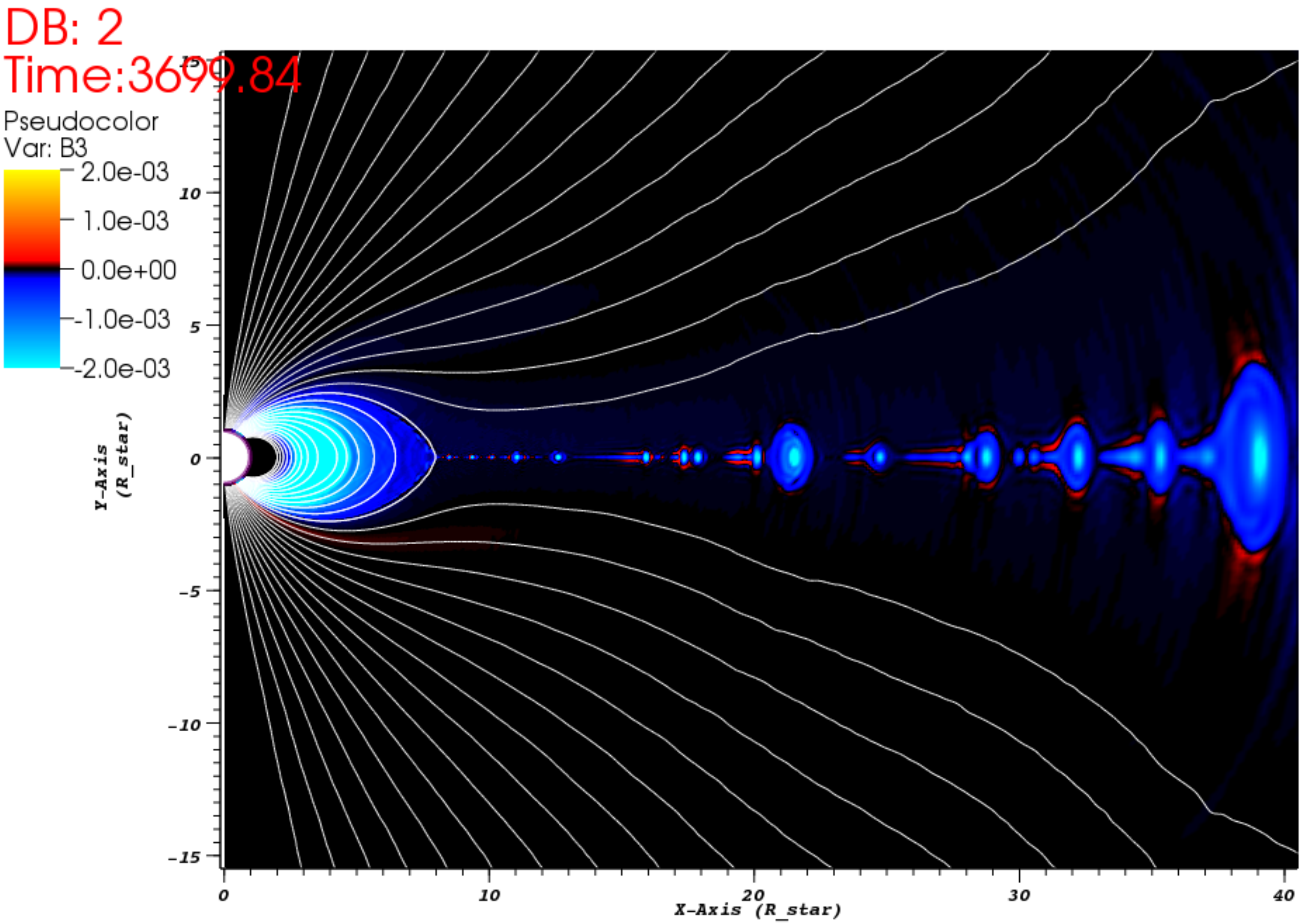

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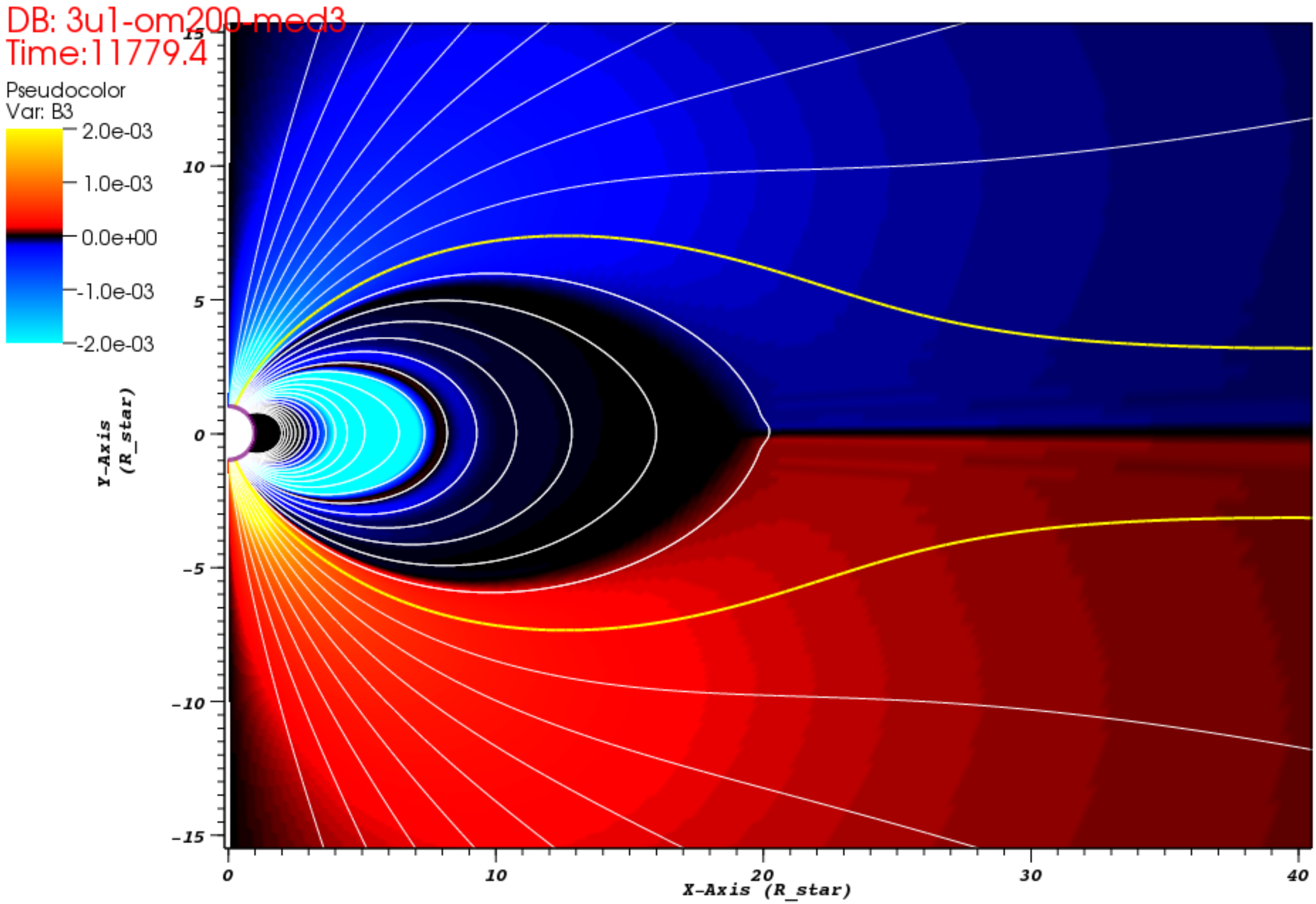
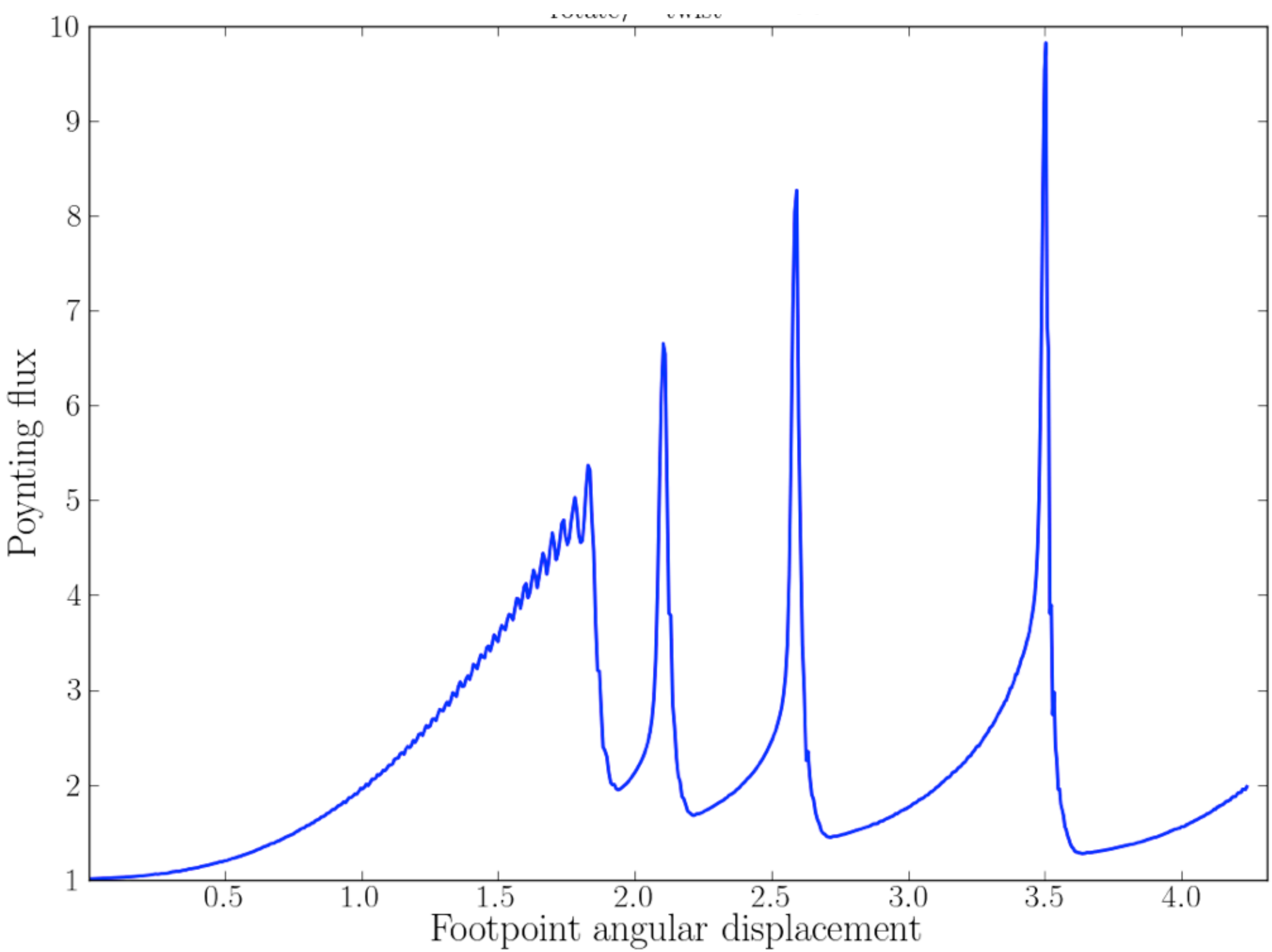
Spindown

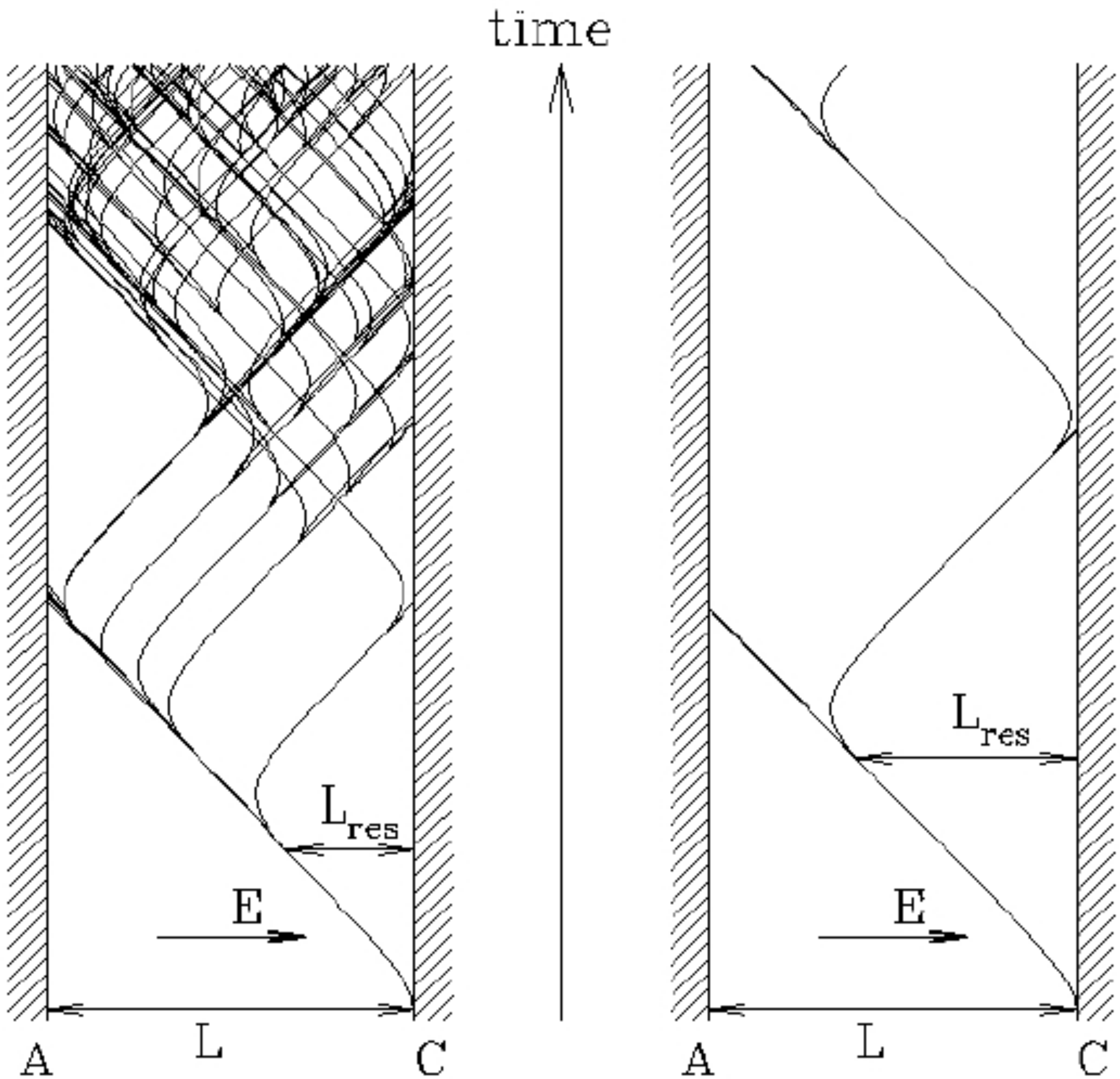

DB: 3u1-om200-med3
Time:11779.4
Pseudocolor
Var: B3
2.0e-03
1.0e-03
0.0e+00
-1.0e-03
-2.0e-03
Y-Axis (R_star)
X-Axis (R_star)
15
10
5
0
-5
-10
-15
0
10
20
30
40



Poynting flux
Footpoint angular displacement
10
9
8
7
6
5
4
3
2
1
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

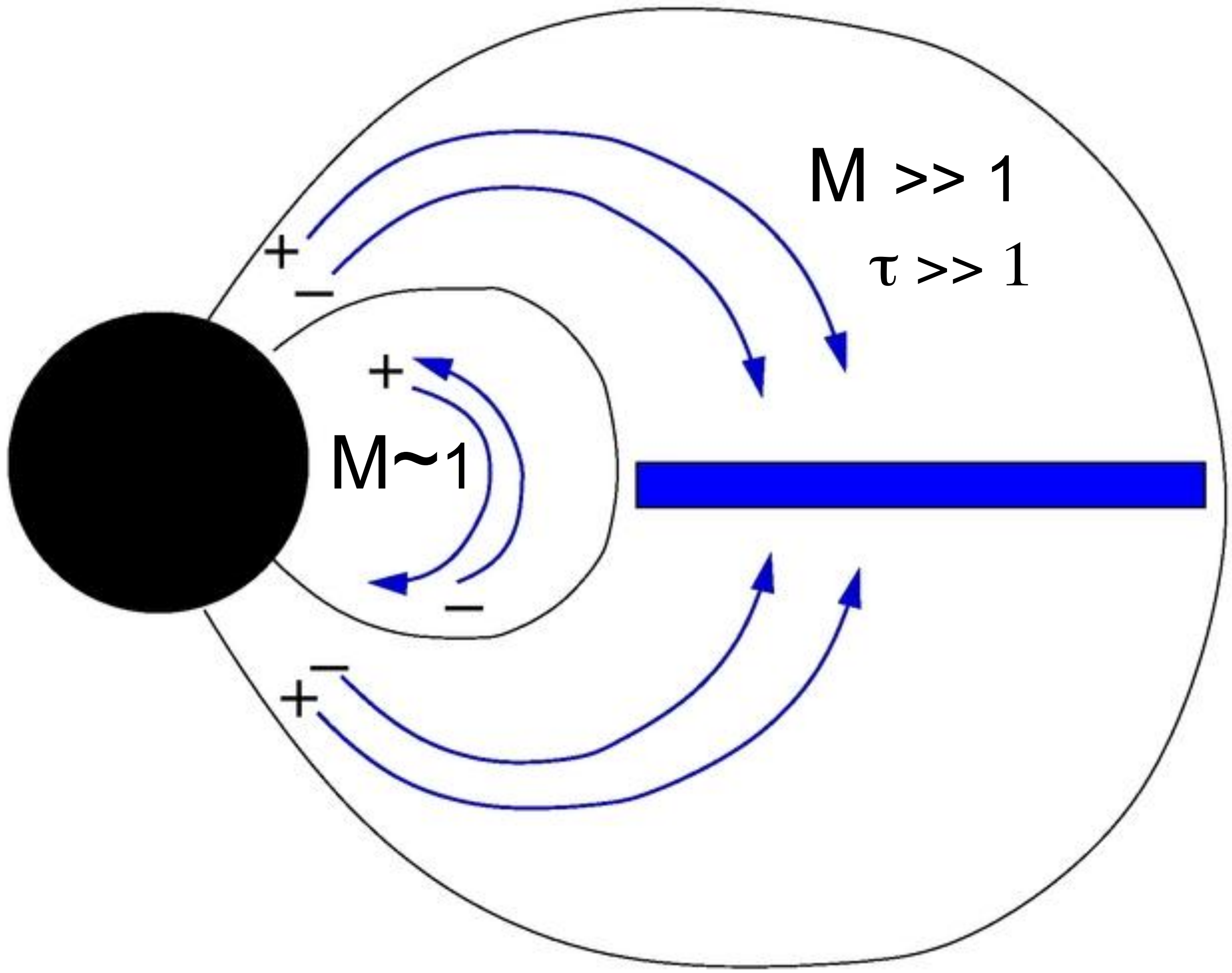
Electron-positron plasma

e+/- breakdown



(a) (b)

Plasma circulation in the magnetosphere



$$\mathrm{M} \equiv \frac{e\dot{N}}{j}$$

$$\sigma_{\mathrm{res}} \approx 2\pi^2 \frac{e^2}{m_{\mathrm{e}}c^2}\frac{c}{\omega}$$

Outer corona: radiative transfer problem

*R*elativistic e^+, e^- are injected in the strong-field region $B > B_Q$,

$$L_\pm \sim I\Phi \sim 10^{36}\ \Phi_9\ B_{15}\ \psi\ A_{12}^2 \quad \text{erg s}^{-1}$$

Neutron star emits $\approx$ blackbody radiation,

$$L \sim 10^{35}\ \text{erg s}^{-1}$$

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Pair cascade at $B > 0.1 B_Q$: scattered photons convert to pairs,

multiplicity M ~10^2

Radiation field controls the flow momentum

=> self-consistent transfer in the opaque outflow

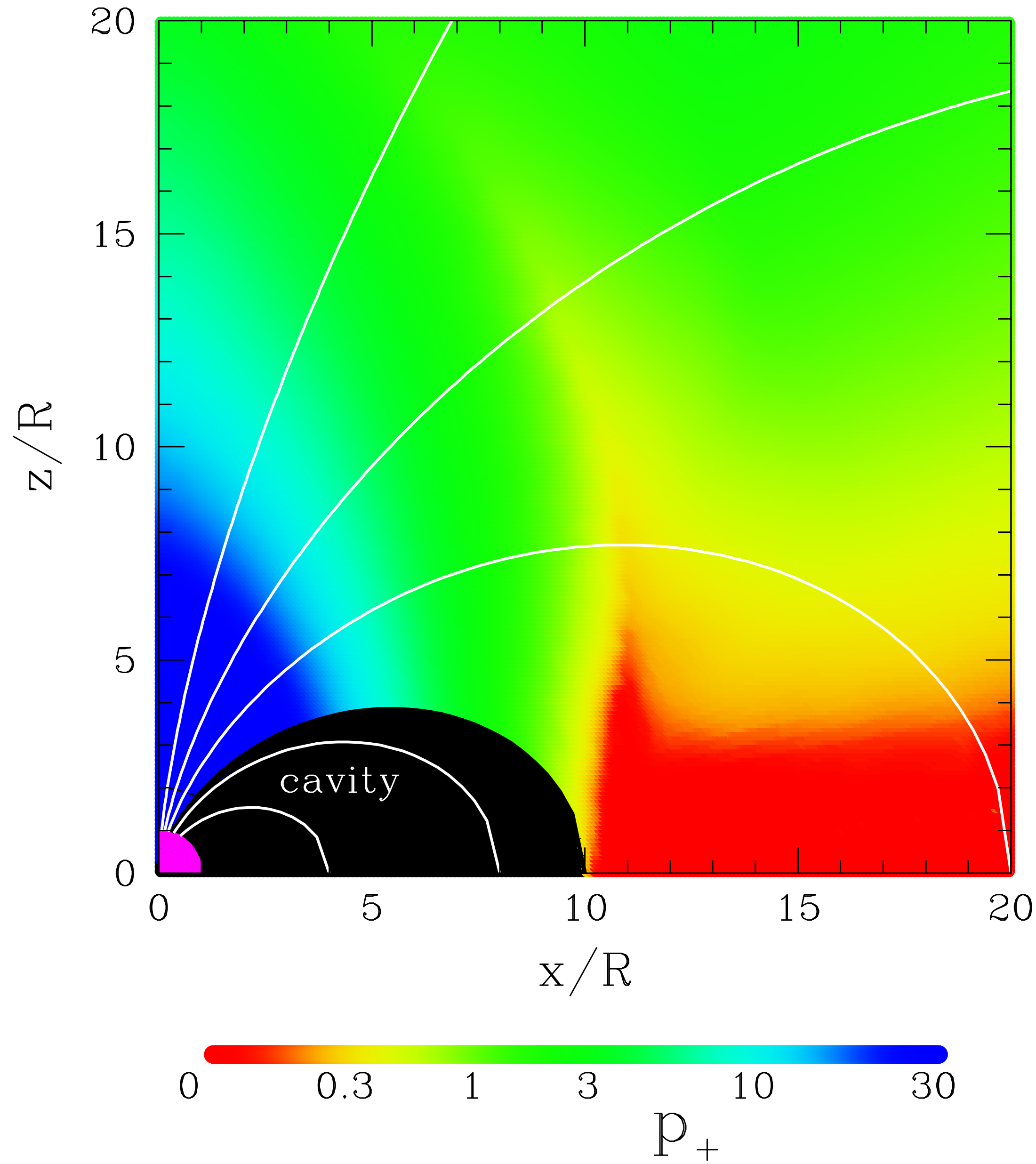
Radiative transfer:

- two polarization states (four Compton cross sections)
- ray tracing
- photon conversion off the field
- synchrotron radiation (turns out unimportant)
- photon splitting (turns out unimportant)
- Self-consistent momentum distribution of e+- ; energy balance

-- main advance compared with previous transfer simulations

(Fernandez, Thompson 2007; Nobili, Turolla, Zane 2008; Fernandez, Davis 2011)

solution



$B_{pole} = 10^{15}$ G

$\psi = 0.3$

$\Phi = 10^9 V$

$kT = 0.3$ keV

(star)

Drag-induced turbulence and low-frequency emission

Radiative locking of electron/positron momenta

Radiative drag force and saturation momentum p_* :

$$F(p_*) = 0, \qquad F(p) > 0 \quad \text{if} \quad p < p_*$$

$$F(p) < 0 \quad \text{if} \quad p > p_*$$

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Nearly neutral plasma $n_+ \approx n_-$; electric current $j \neq 0 \;\Rightarrow\; p_+ \neq p_-$

$$\frac{\mathrm{v}_-}{\mathrm{v}_+} = \frac{\mathrm{M}-1}{\mathrm{M}+1} \qquad (\text{multiplity } \mathrm{M} \equiv \frac{e\dot{N}}{j})$$

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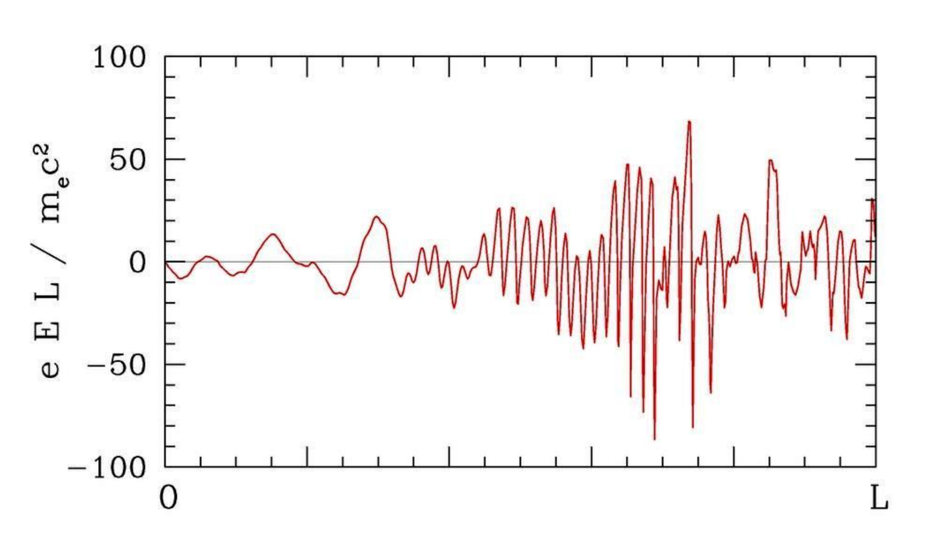
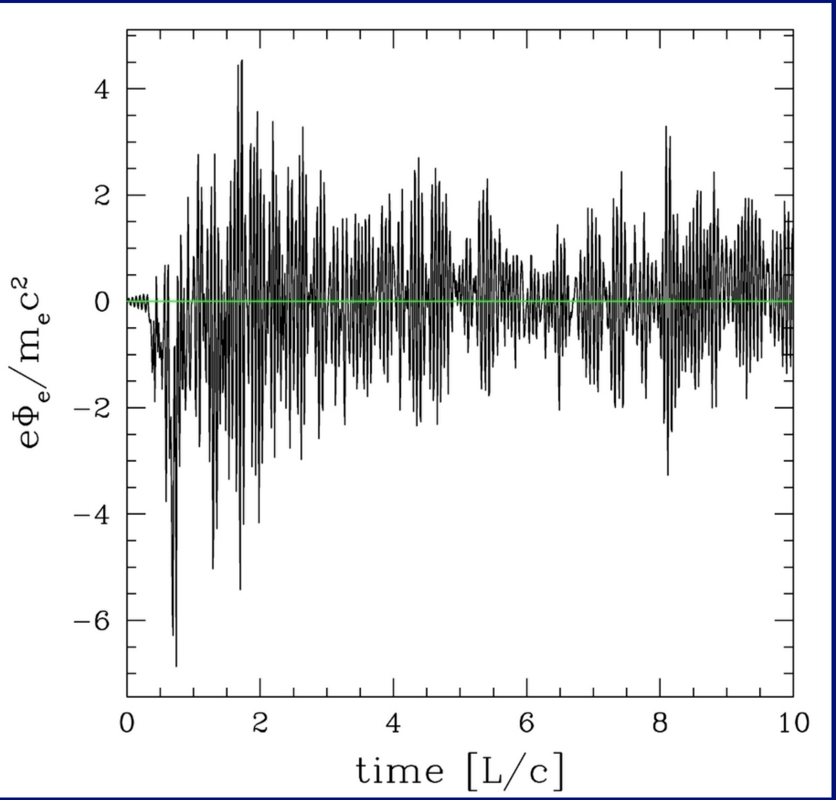
two-fluid model: $$\frac{dp_+}{dt} = F(p_+) + eE_{\|}$$

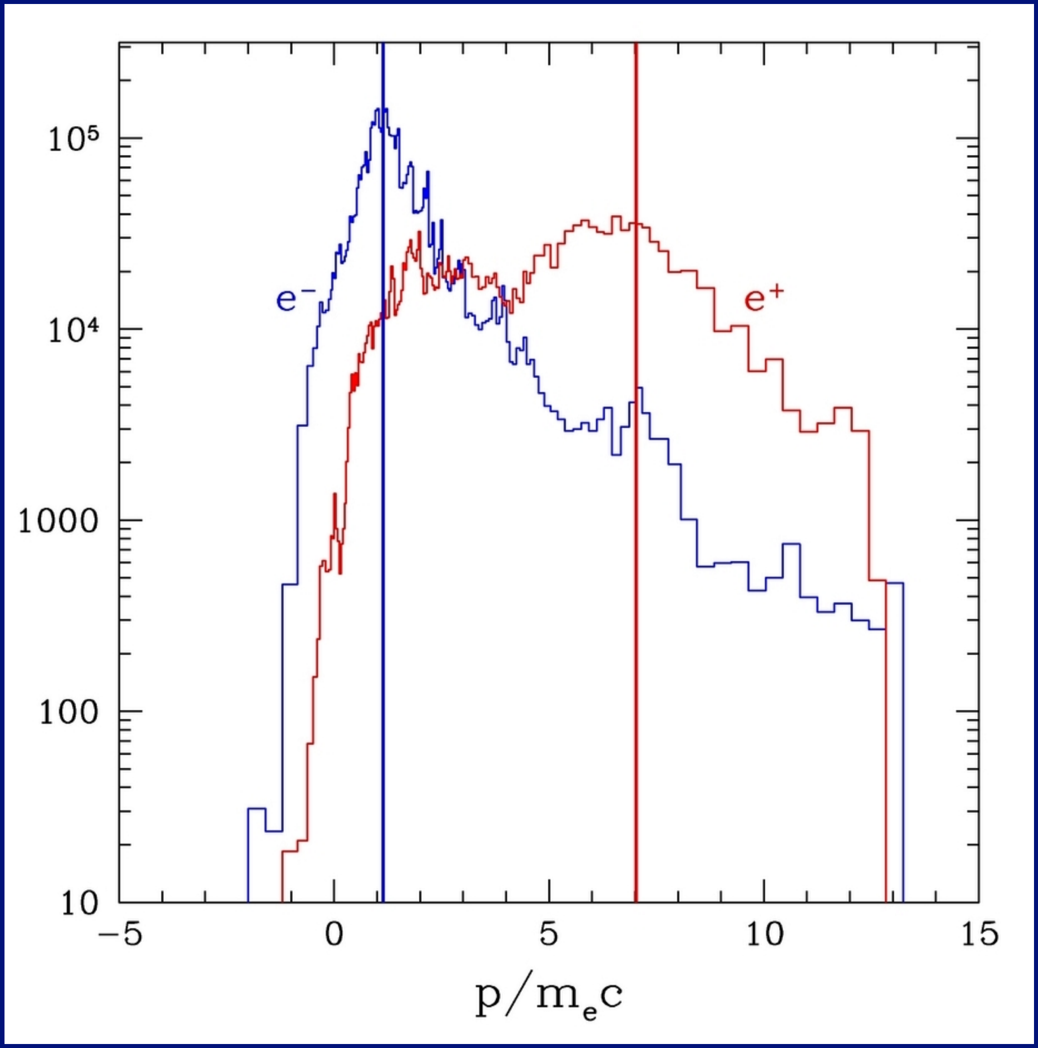
$$\frac{dp_-}{dt} = F(p_-) - eE_{\|}$$

Two-stream instability in the outflow





Spread in momentum of e+-



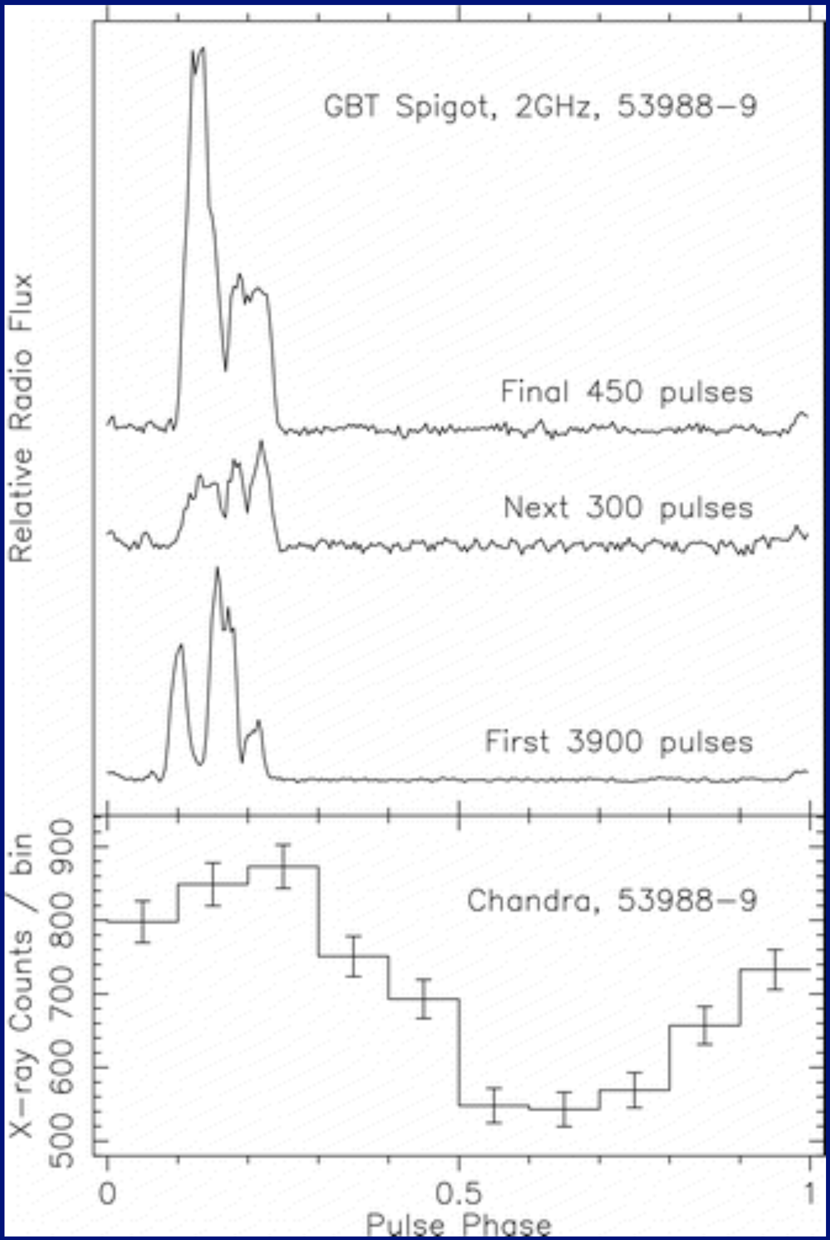
Radio pulsations from XTE J1810-197

-- switched on after the starquake

-- radio luminosity ~ 2x10^30 erg/s. Rotationally powered?

$$I_{\mathrm{lc}}\Phi \sim 10^{28}(e\Phi/\mathrm{GeV})\ \mathrm{erg/s}$$

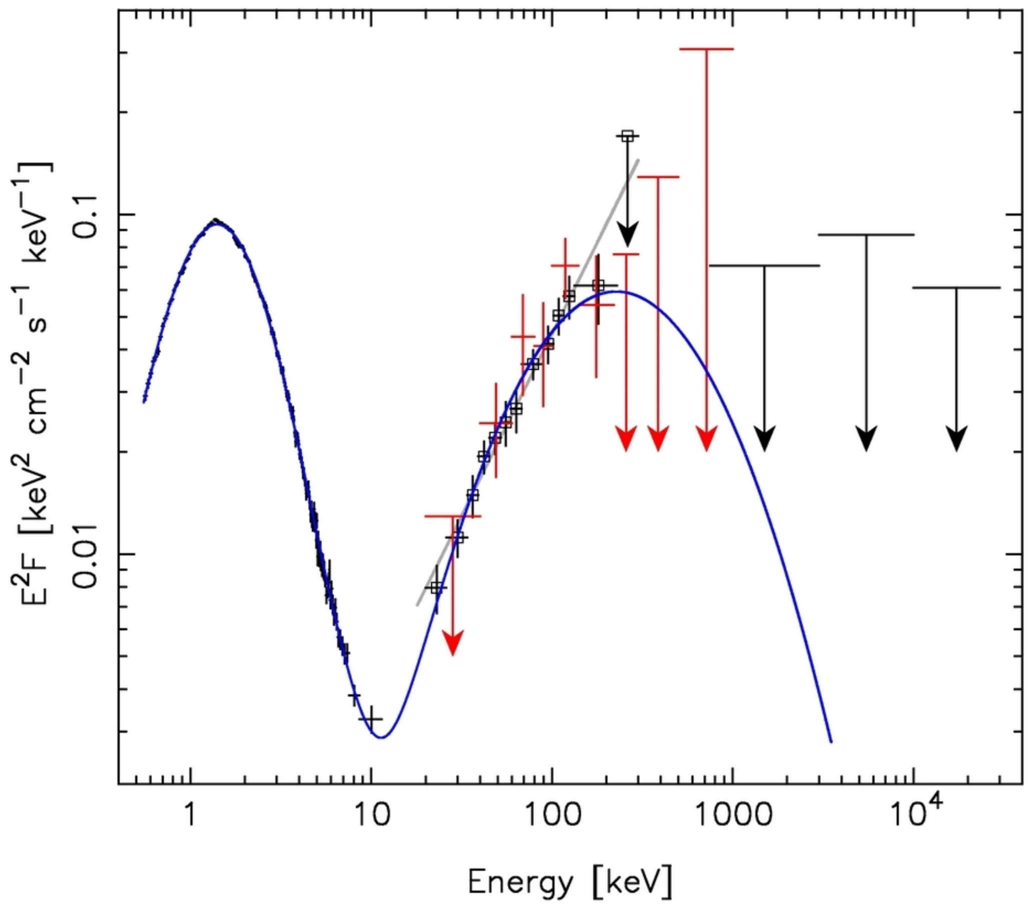
-- radio waves and X-rays probably come from the same bundle of field lines (simultaneous pulses)

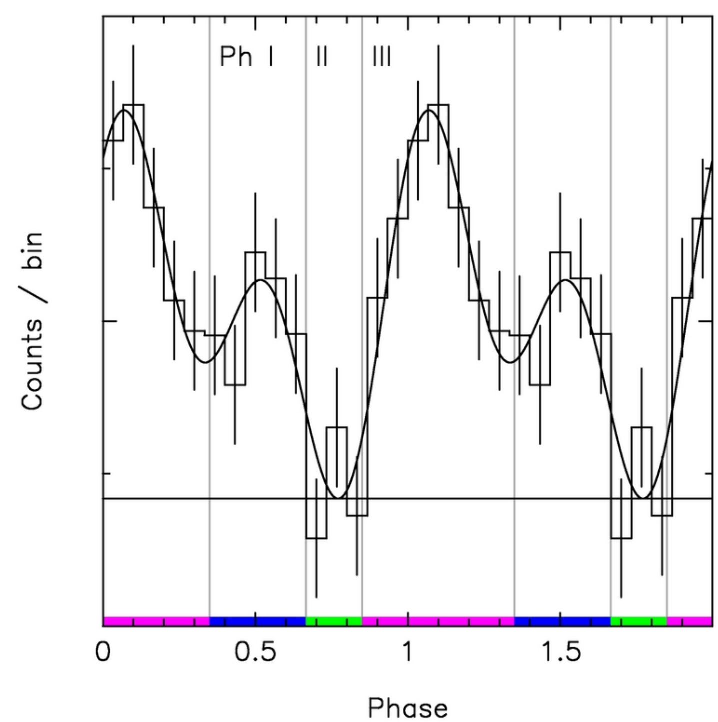


Camilo et al. 2007

Nonthermal X-ray emission

AXP 4U 0142+61





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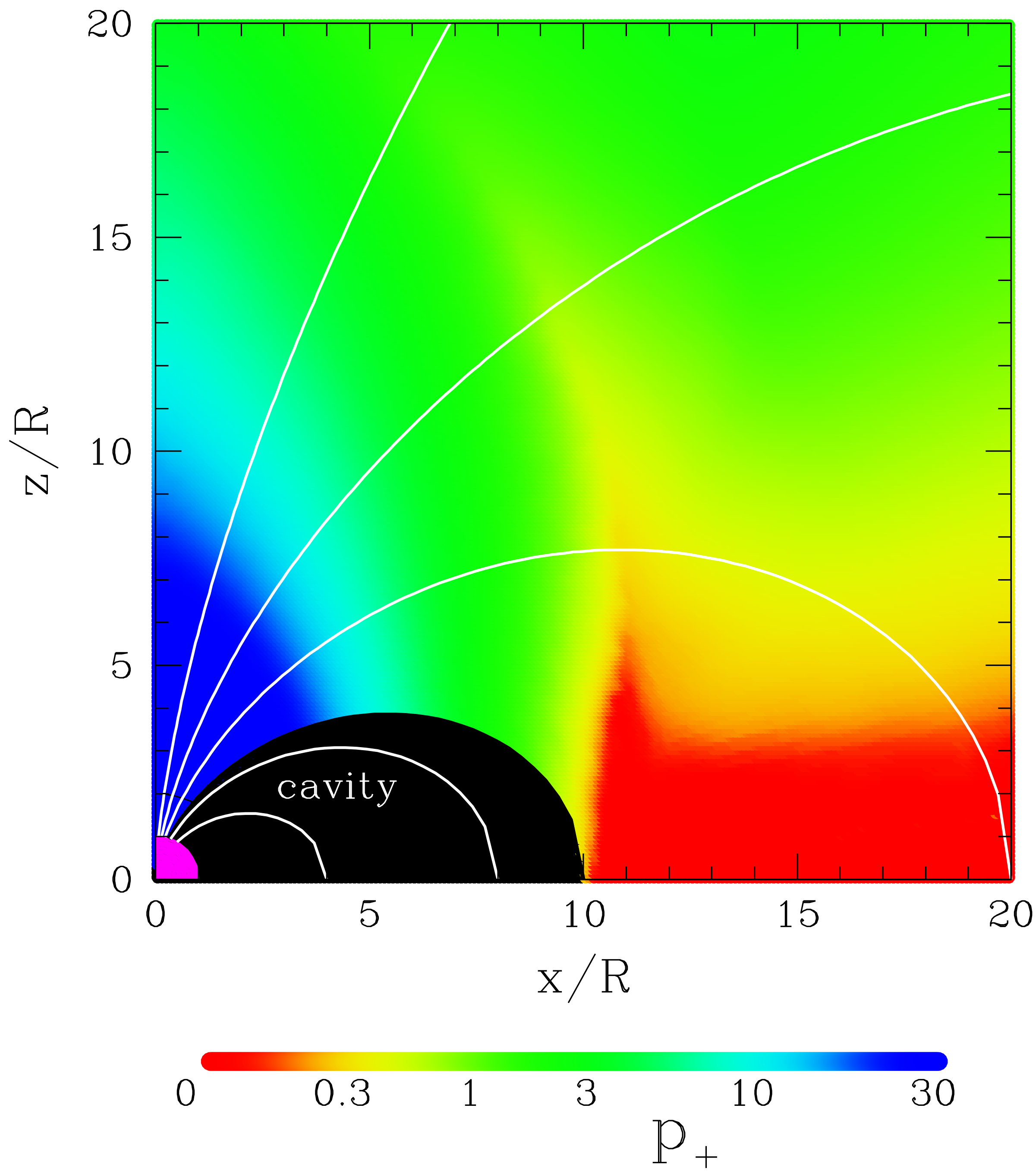
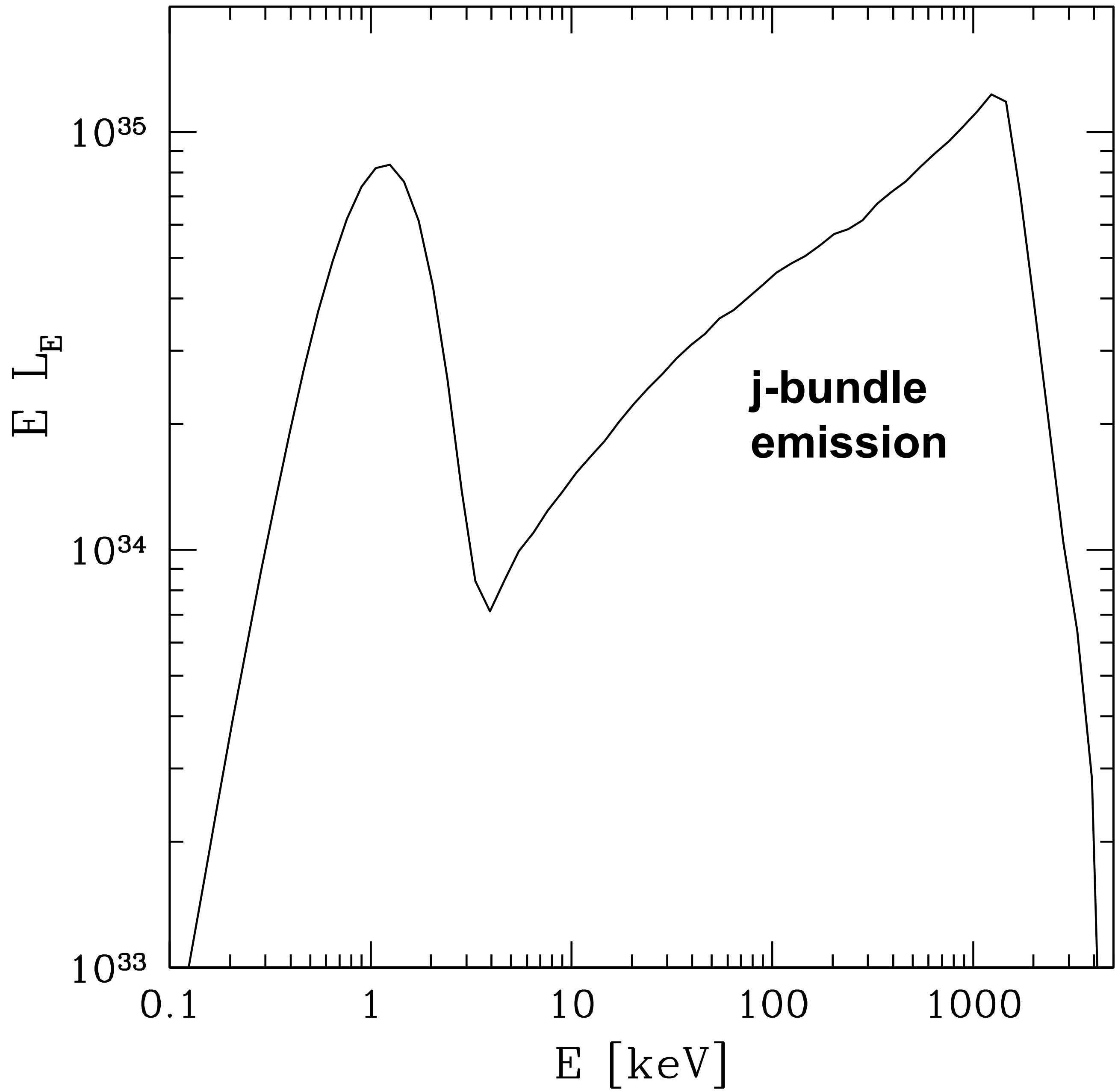
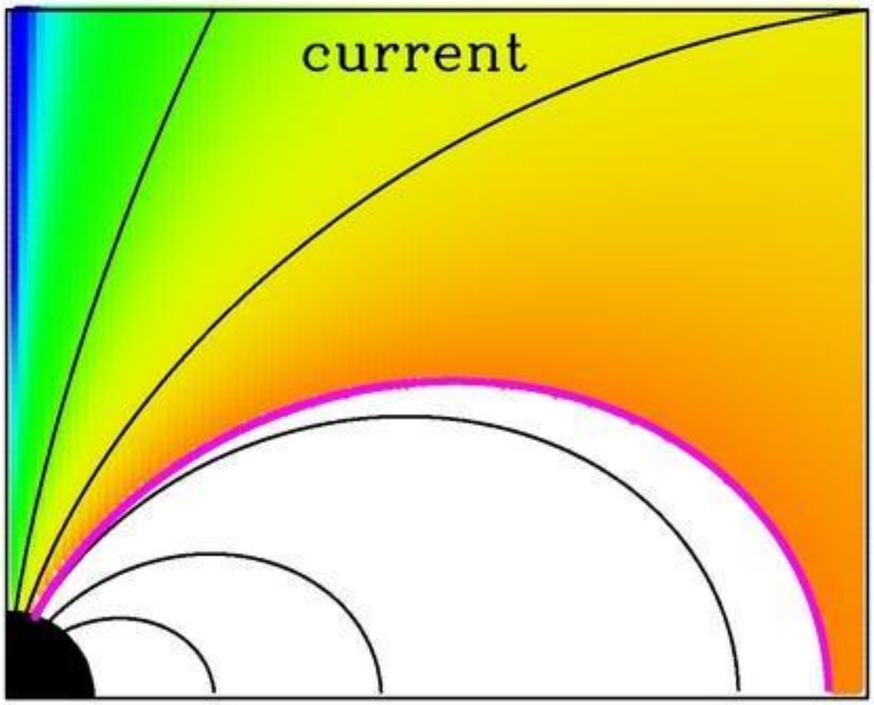


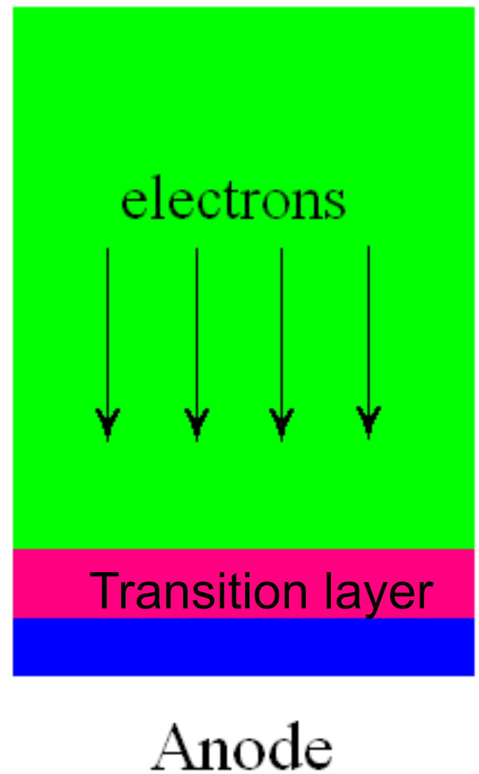
cavity
x/R
z/R
0
5
10
15
20
0
0.3
1
3
10
30
p_+



j-bundle
emission
10^{35}
10^{34}
10^{33}
0.1
1
10
100
1000
E [keV]
$E\,L_E$

Heated footprint





Transition layer: kT ~ 200 keV

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- A high-multiplicity e+- outflow (M~100) forms in the j-bundle.
  It emits hard X-rays and stops in the equatorial plane.

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- Radiative drag induces turbulence and low-frequency emission