Inflowing matter - magnetosphere interaction in compact stars

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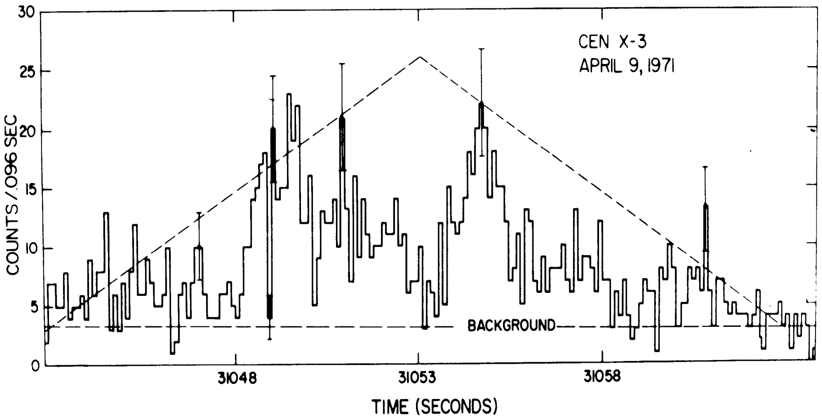
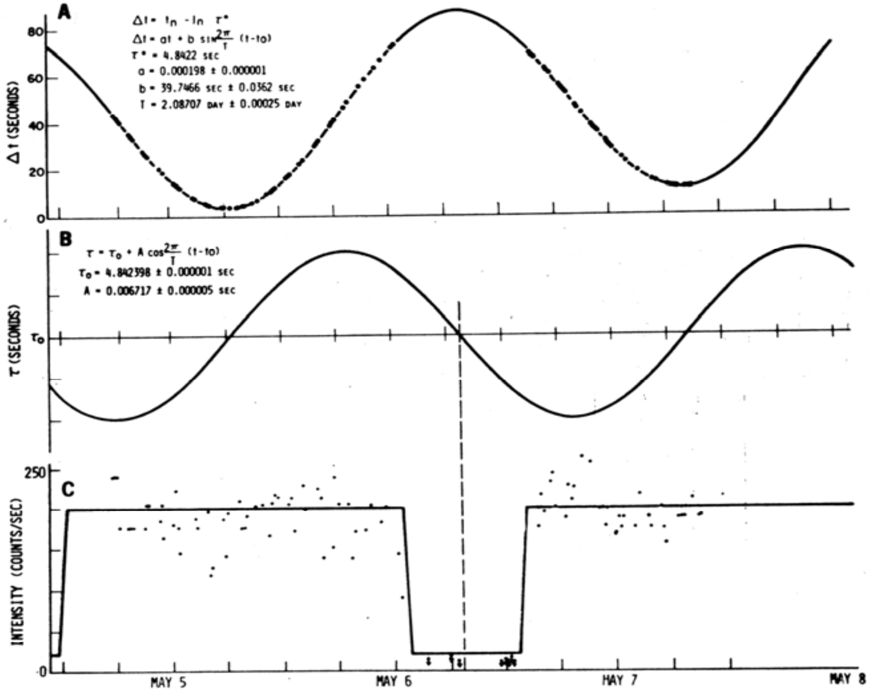
Outline

- Basics
- Different regimes for a rotating magnetosphere
- Propeller regime and jet production
- Accretion torques

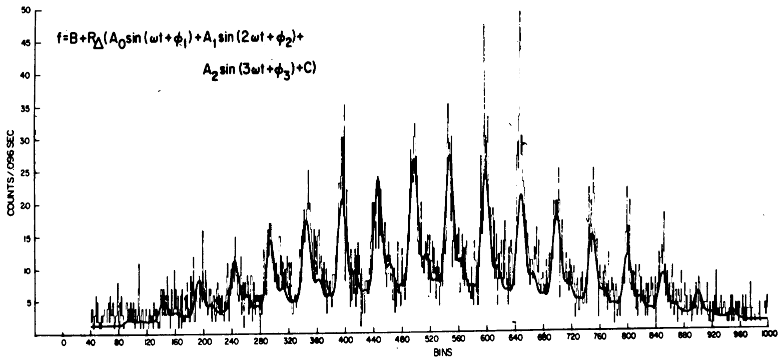
Uhuru 1971: Cen X-3





CENTAURUS X-3 (2ASE 1119 –60)

May 7, 1971



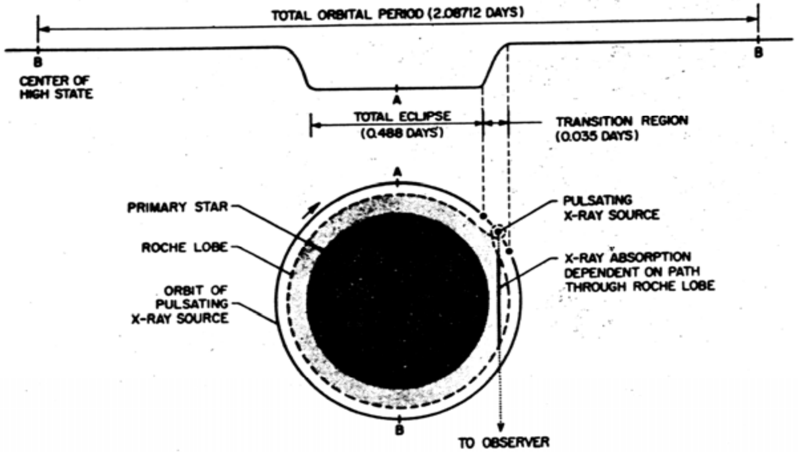
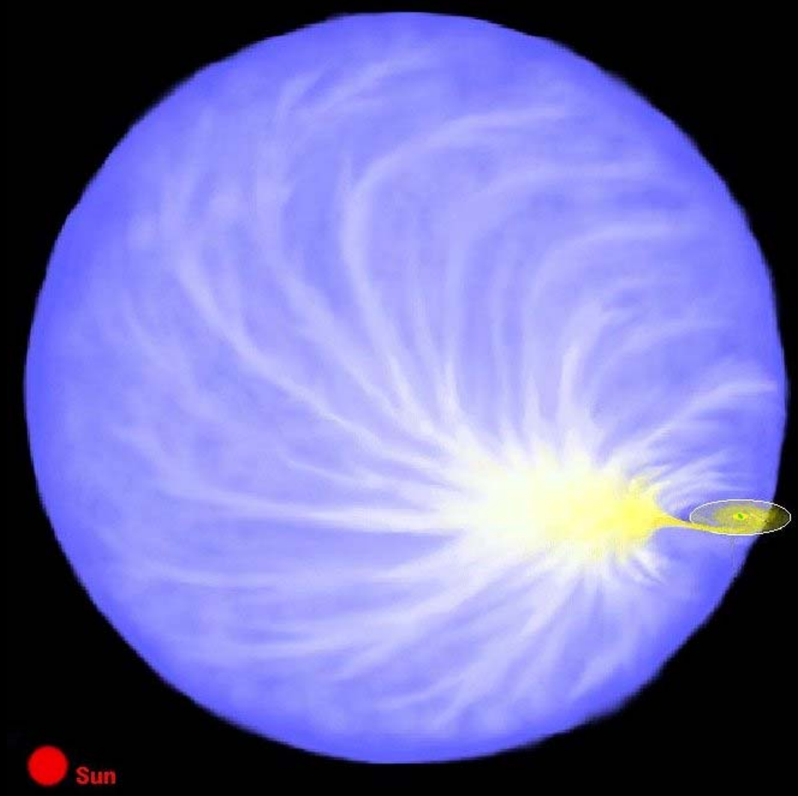
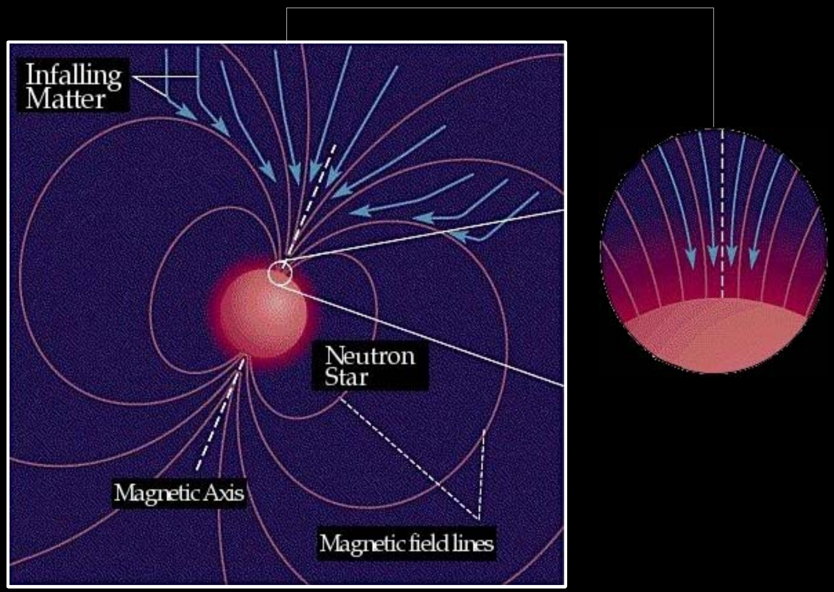
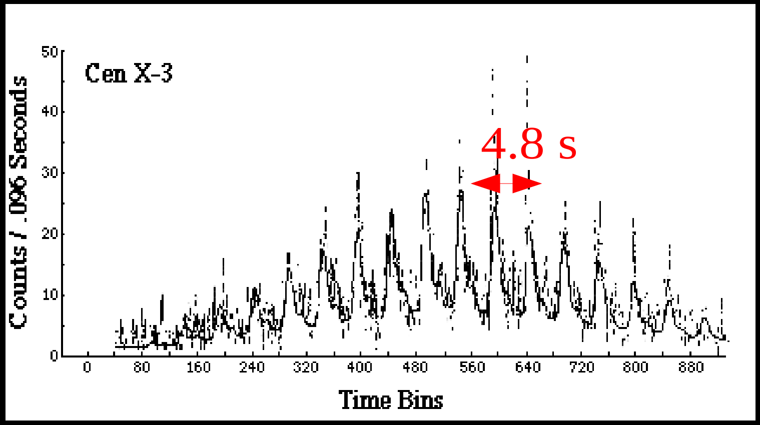


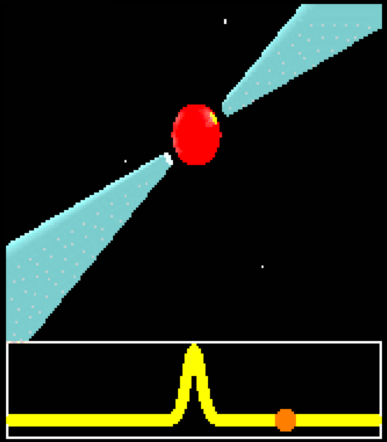
Fig. 8. – Schematic representation of occulting binary X-ray system.

Cen X-3





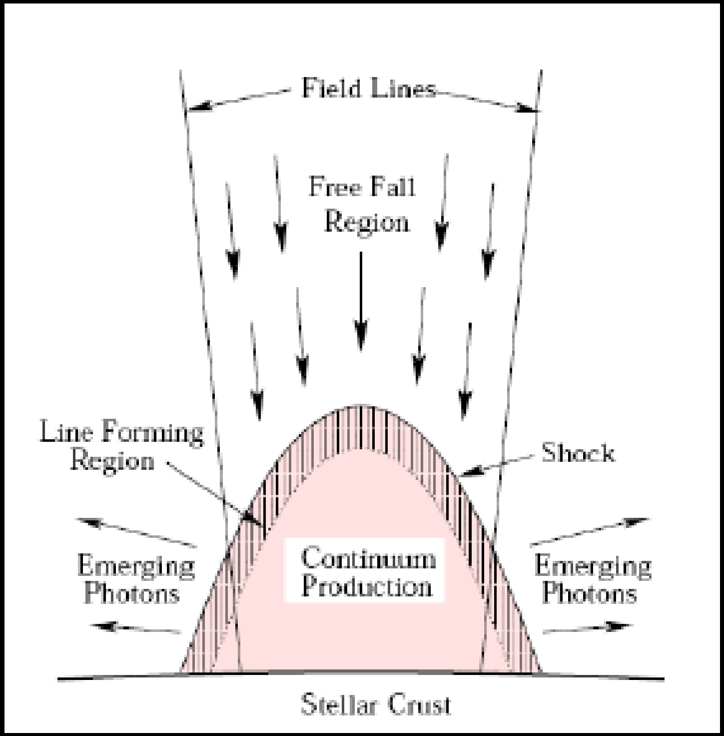




$$L_{acc} \sim \frac{G M_{NS} \dot{M}}{R_{NS}}$$

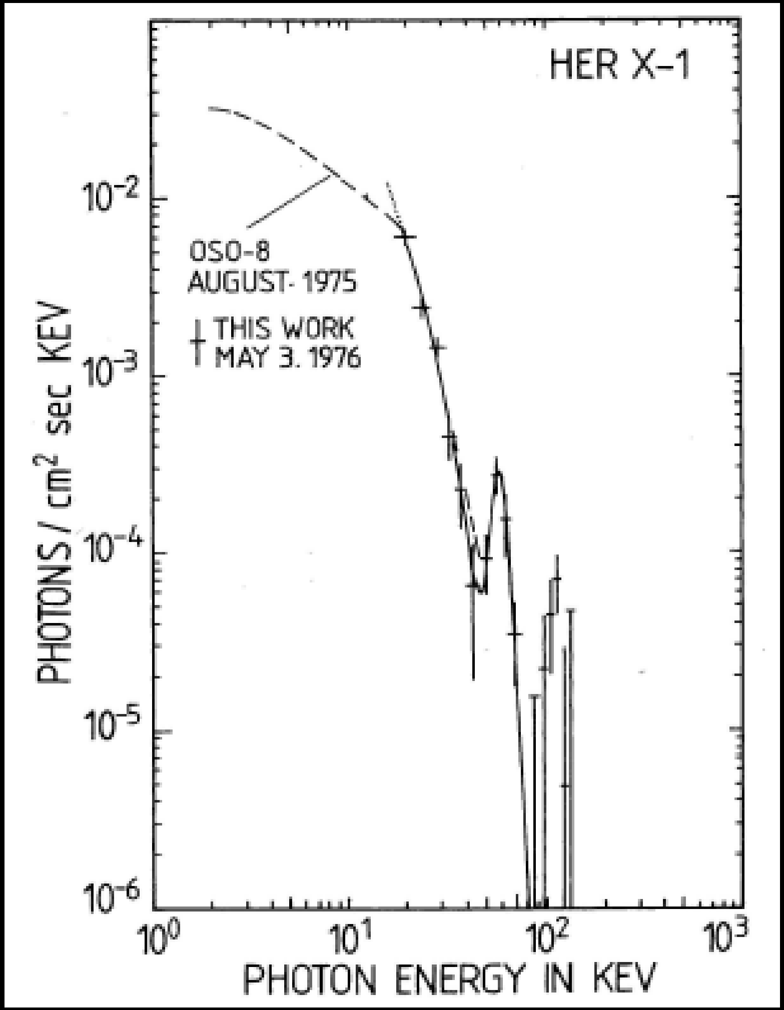
$$10^{36} - 10^{38}\, erg\, s^{-1}$$

Cyclotron Lines



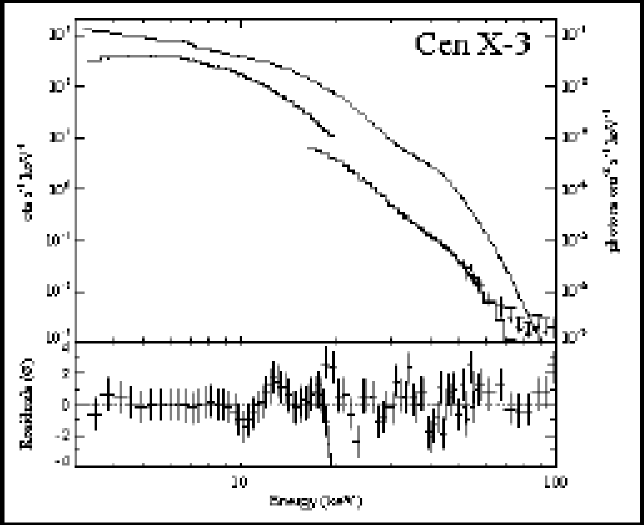
$$E_{cyc} \simeq \hbar \omega_B = \hbar \frac{eB}{m_e}$$

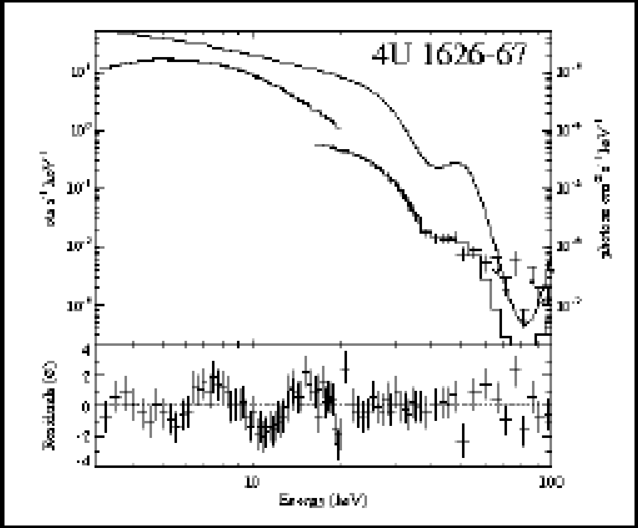
$$E_{cyc} \simeq 11.6 \ \frac{B}{10^{12} \ G} \ keV$$

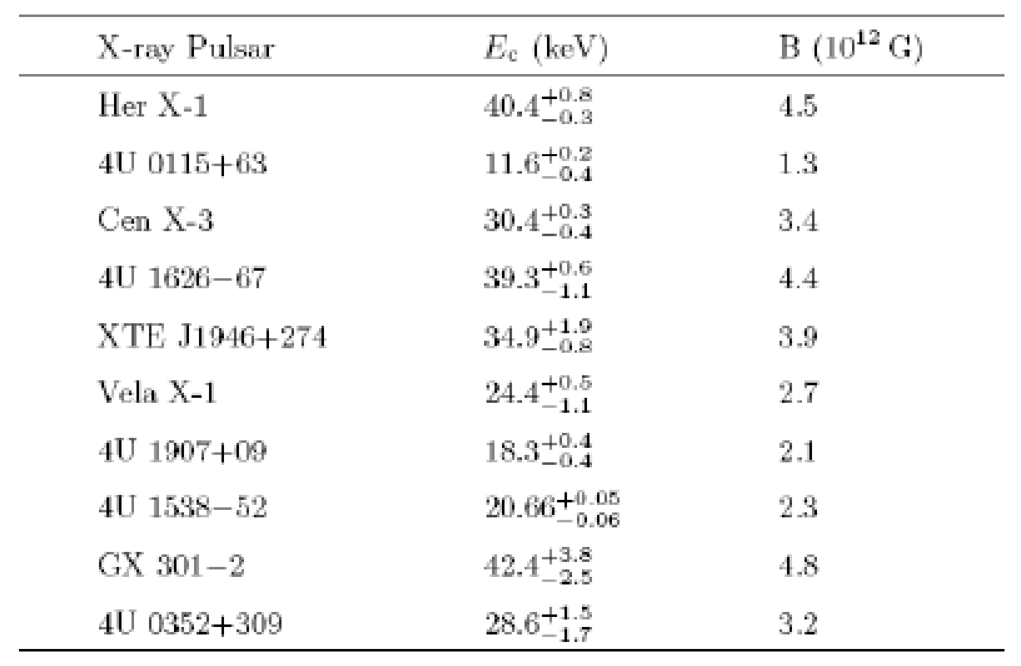


Her X-1: First Detection of a cyclotron line (balloon experiment,, Trumper 1978)

Other Examples







X-ray Pulsar	E_c (keV)	B (10^{12} G)
Her X-1	$40.4^{+0.8}_{-0.3}$	4.5
4U 0115+63	$11.6^{+0.2}_{-0.4}$	1.3
Cen X-3	$30.4^{+0.3}_{-0.4}$	3.4
4U 1626−67	$39.3^{+0.6}_{-1.1}$	4.4
XTE J1946+274	$34.9^{+1.9}_{-0.8}$	3.9
Vela X-1	$24.4^{+0.5}_{-1.1}$	2.7
4U 1907+09	$18.3^{+0.4}_{-0.4}$	2.1
4U 1538−52	$20.66^{+0.05}_{-0.06}$	2.3
GX 301−2	$42.4^{+3.8}_{-2.5}$	4.8
4U 0352+309	$28.6^{+1.5}_{-1.7}$	3.2

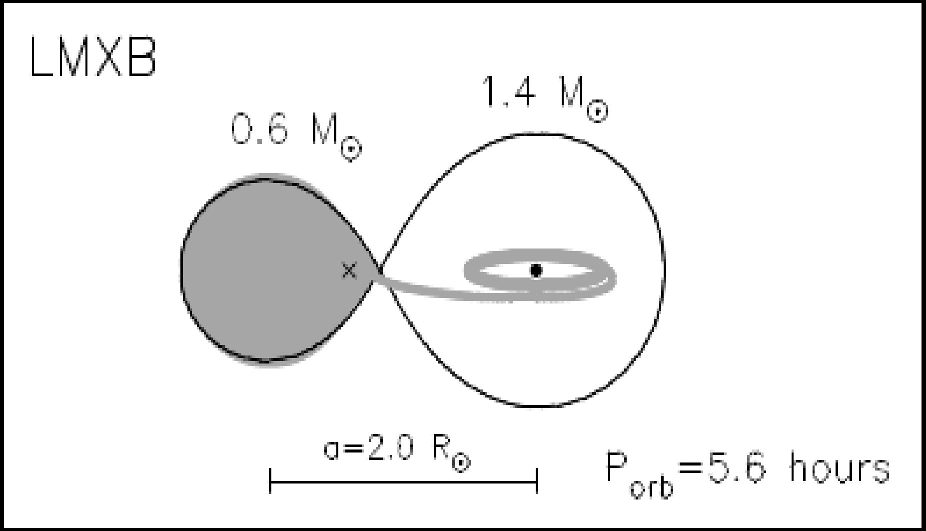
Mass Transfer in X-ray Binaries

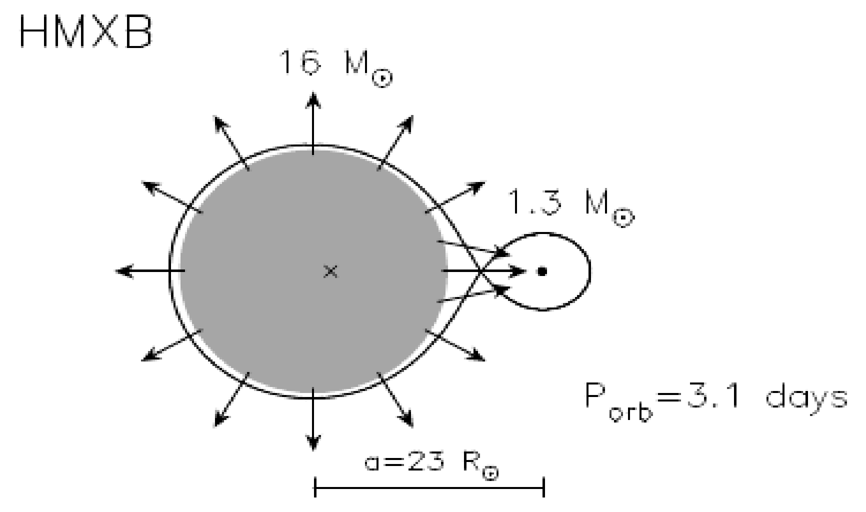
Roche Lobe overflow:
high specific angular momentum

Wind capture:
Low specific angular momentum

LMXB (low mass X-ray binaries)

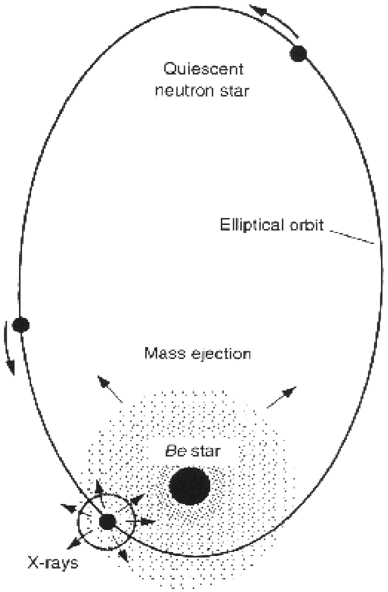
HMXB (high mass X-ray binaries)



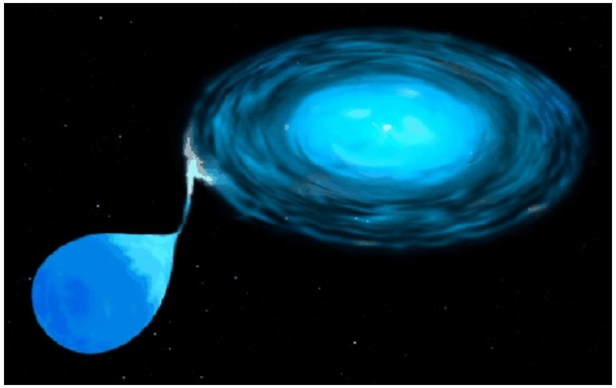


XRTs : spectral classification

Hard XRTs: young X-ray pulsating NSs in Be star binaries



Soft XTRs: old (bursting) NSs in low mass X-ray binaries



Ultrasoft XTRs: black hole candidates in low mass X-ray binaries

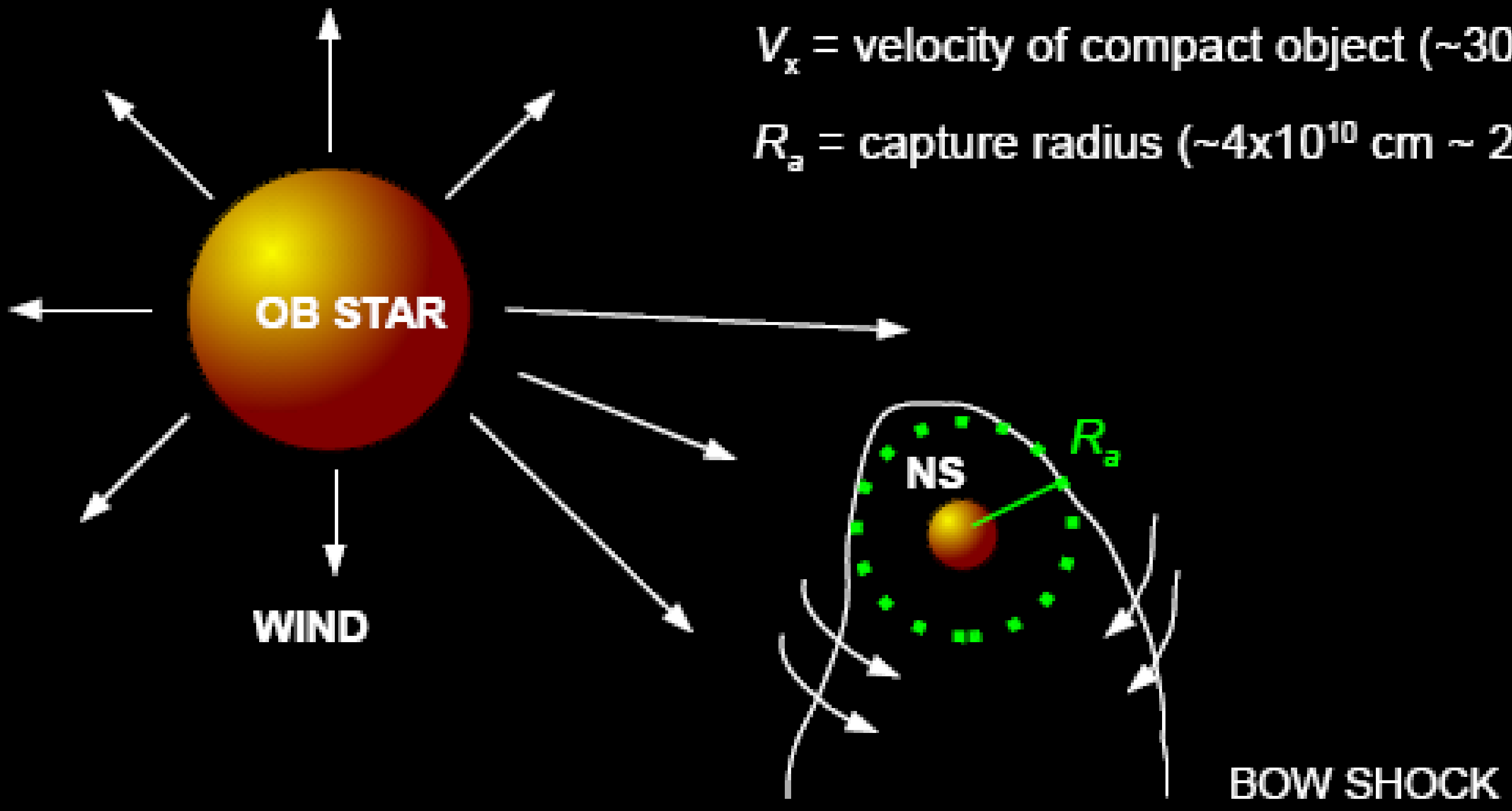
(White, Kaluzienski, Swank 1984)

Accretion Radius: R_a

V_w = wind velocity (~1000 Km s^{-1})

V_x = velocity of compact object (~300 Km s^{-1})

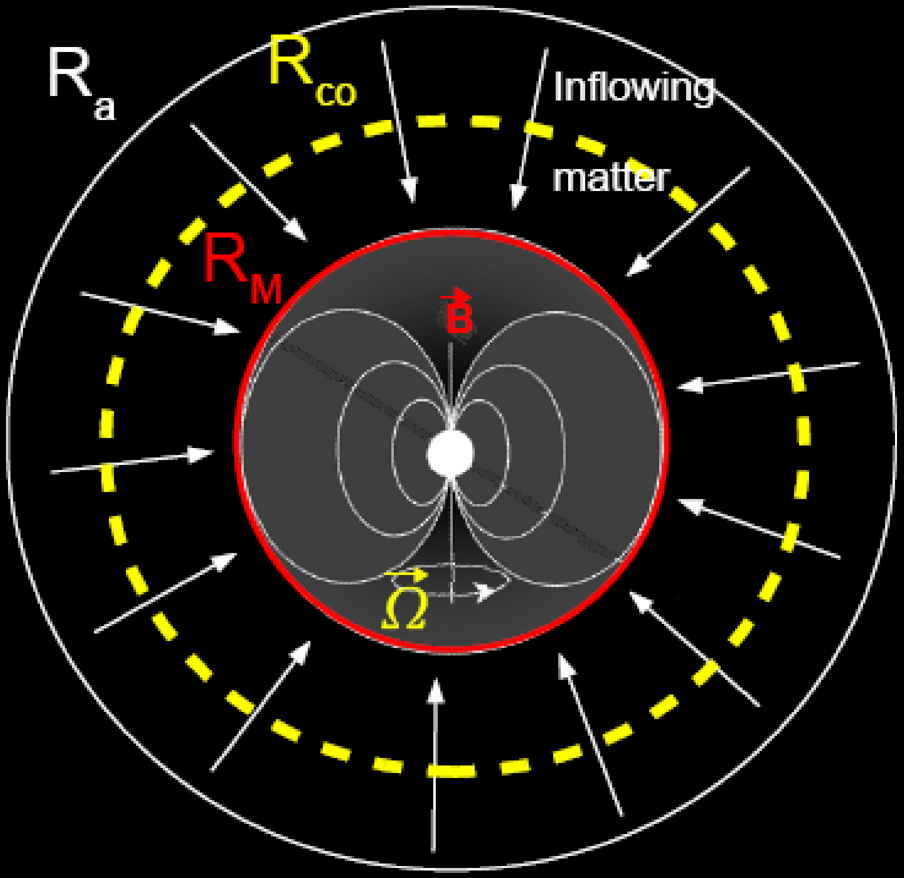
R_a = capture radius (~4×10^{10} cm ~ 2-3 R_*)



$$R_a = \frac{2\,GM_X}{V_X^2 + V_W^2} \sim \frac{2\,GM_X}{V_W^2} \sim 4\times10^{10}\,cm$$

$$\dot{M}_{capt} / \dot{M}_w \sim 10^{-5}$$

Characteristics radii



Magnetospheric Radius: r_m

$$P_{mag}(r) = \frac{B^2(r)}{8\pi} = P_{ram}(r) = \rho(r) v_{in}^2(r)$$

$$\dot{M}_{acc} = 4\pi r^2 \rho(r) v_{in}^2$$

$$r_m = \left(\frac{1}{2}\xi\right)^{1/2} \mu^{4/7} (2GM_X)^{1/7} \dot{M}_{acc}^{-2/7}$$

$$r_m = 2.9\times10^8 \mu_{30}^{4/7} m^{1/7} R_6^{-2/7} L_{37}^{-2/7}\, cm$$

Corotation Radius: r_{co}

$$r_{co} = \left(\frac{GM_X}{\Omega_s^2}\right)^{1/3} = 1.5\times10^8 m^{1/3} P_s^{2/3}\, cm$$

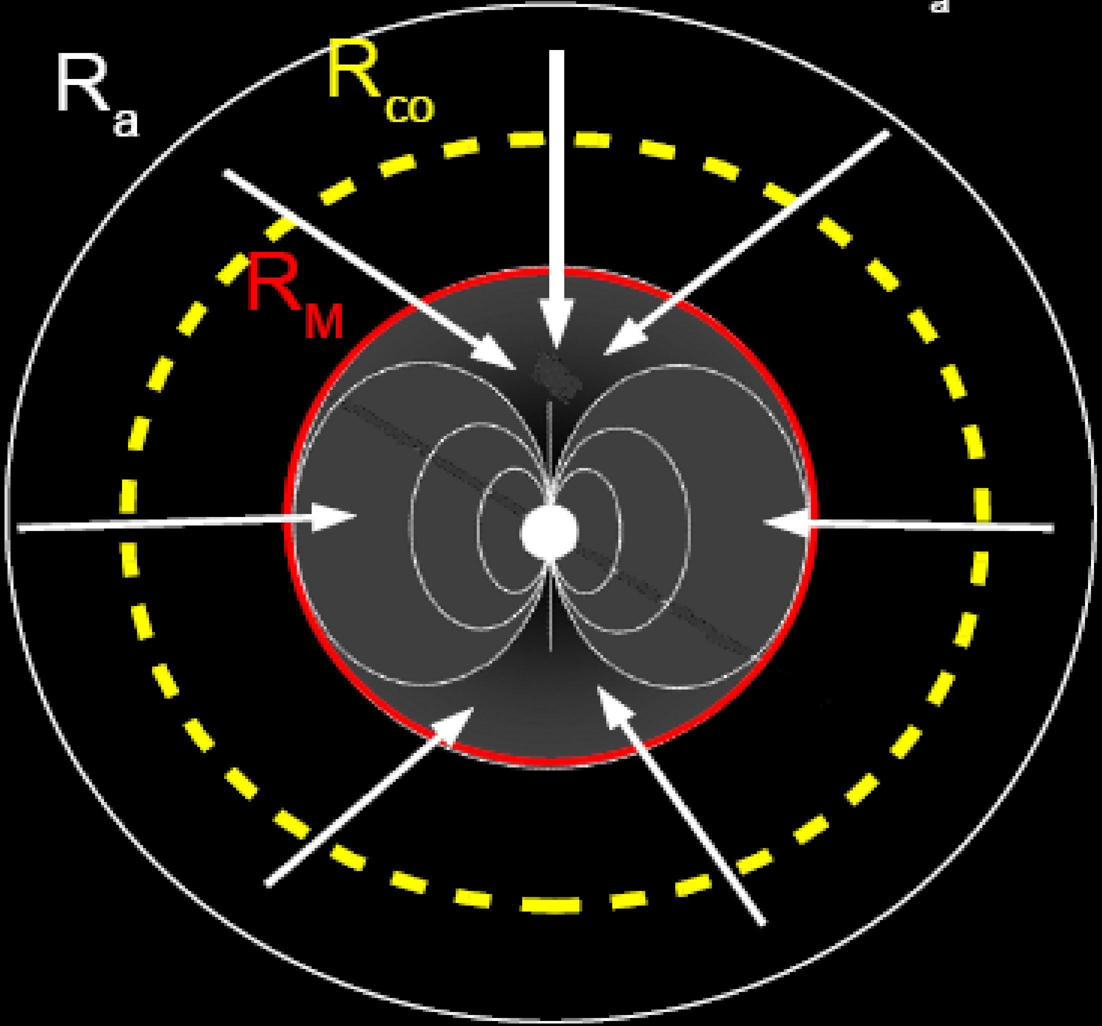
Different relative position of these radii -> Different regimes

(Illarionov & Sunyaev 1975, Stella, White & Rosner 1986)

DIRECT ACCRETION REGIME

$R_M \sim 3\times10^9\, B_{12}^{1/3}\, \dot{M}_{-6}^{-1/6}$ cm $<$ $R_{co} \sim 4\times10^9\, P_{spin100}^{2/3}$ cm

$R_a \sim 4\times10^{10}\, v_8^{-2}$ cm

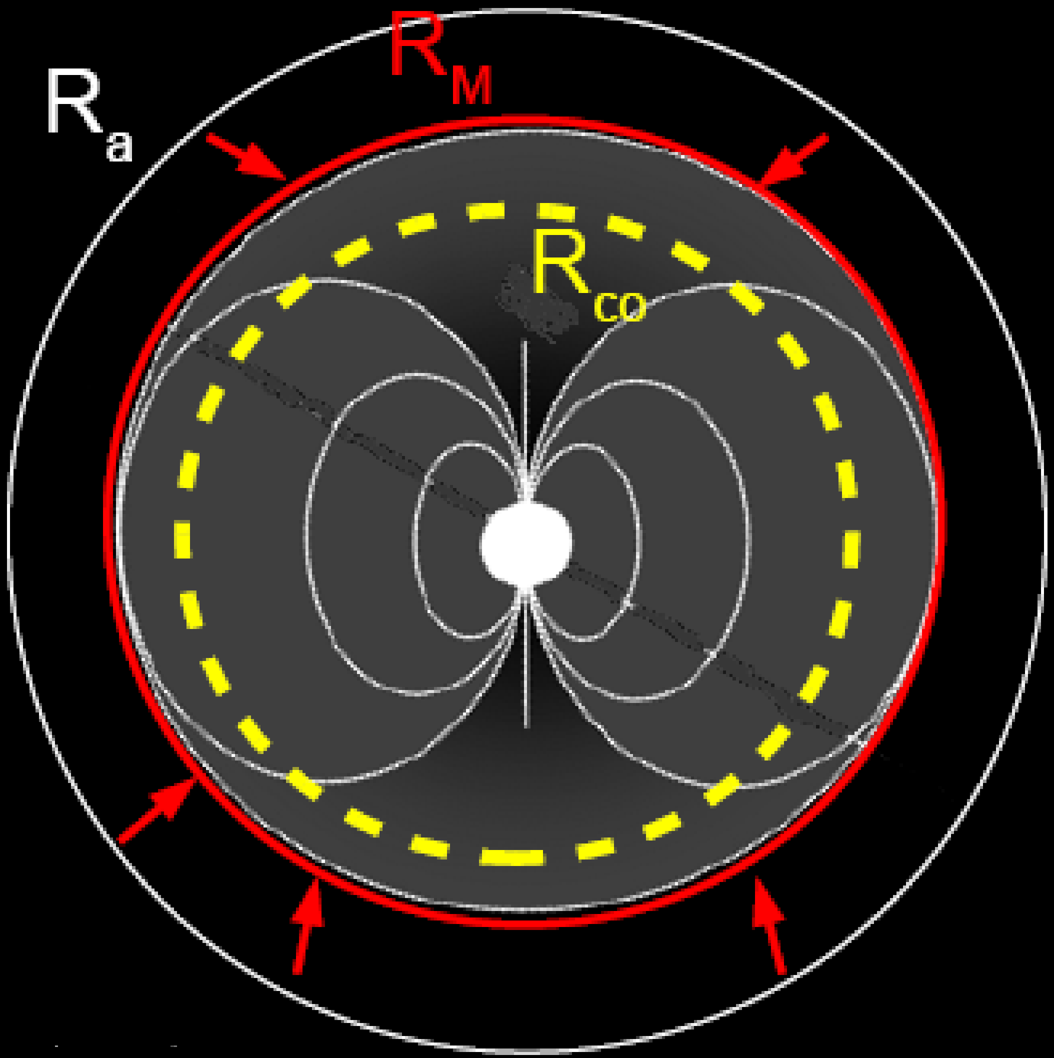


$$L_{acc} \sim \frac{G M_{NS} \dot{M}_{capt}}{R_{NS}}$$

CENTRIFUGAL INHIBITION OF ACCRETION: The Centrifugal barrier (“Propeller”)

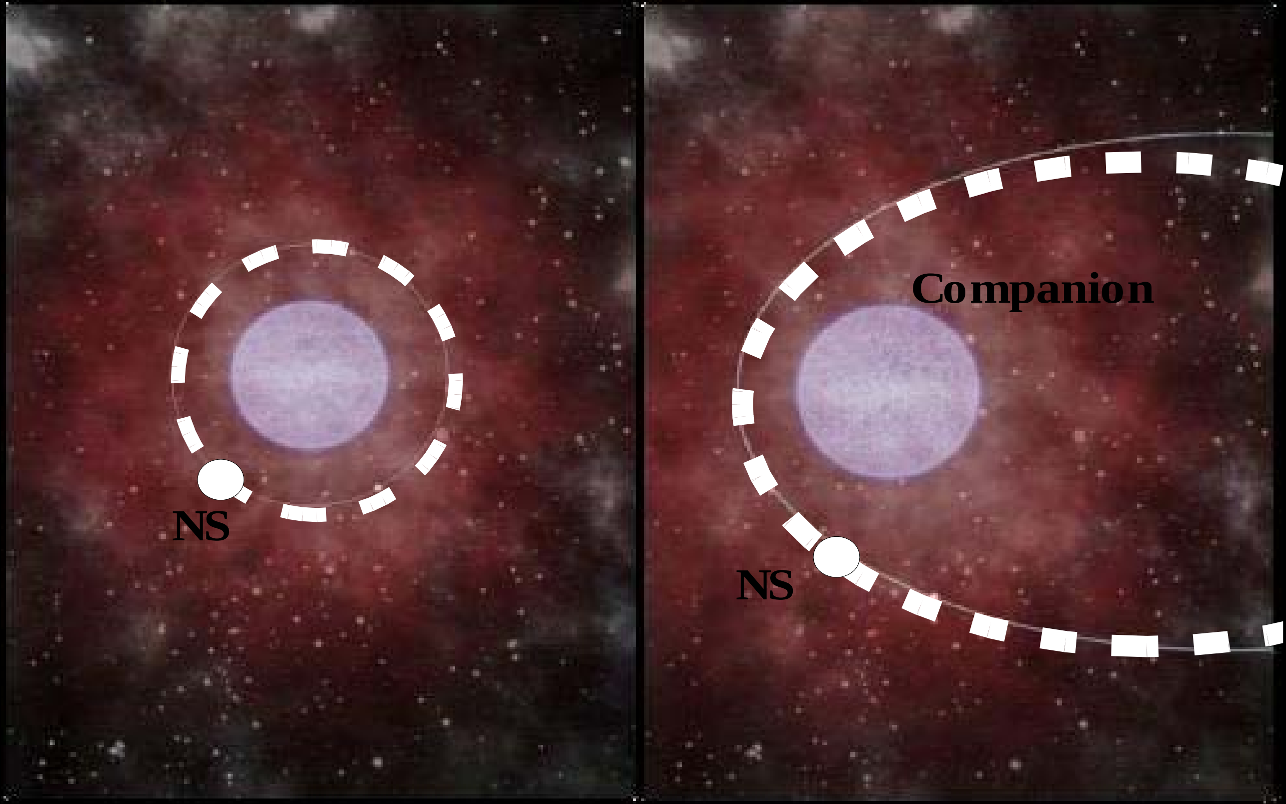
$R_M \sim 4.4\times10^{9}\, B_{12}^{1/3}\, \dot{M}_{-7}^{-1/6}$ cm $> R_{co} \sim 4\times10^{9}\, P_{spin100}^{2/3}$ cm

$< R_a \sim 4\times10^{10}\, v_8^{-2}$ cm



$$L_{pro} \sim \frac{GM_{NS}\dot{M}_{capt}}{R_M} =$$

$$= L_{acc}\frac{R_{NS}}{R_M} \sim 10^{-3} L_{acc}$$



$$L_{acc} \sim \frac{G M_{NS} \dot{M}}{R_{NS}}$$

constant luminosity
10^{35}-10^{38} erg s^{-1}

Transients

variable luminosity
~10^{32}-10^{34} erg s^{-1} (quiescence)
~10^{36}-10^{38} erg s^{-1} (week-to-months long outbursts

X-ray Luminosity Variations: variations of $\dot{M}$ along the orbit
and/or intrinsic variations of wind v_w and n

Onset of centrifugal barrier in Hard XRTs

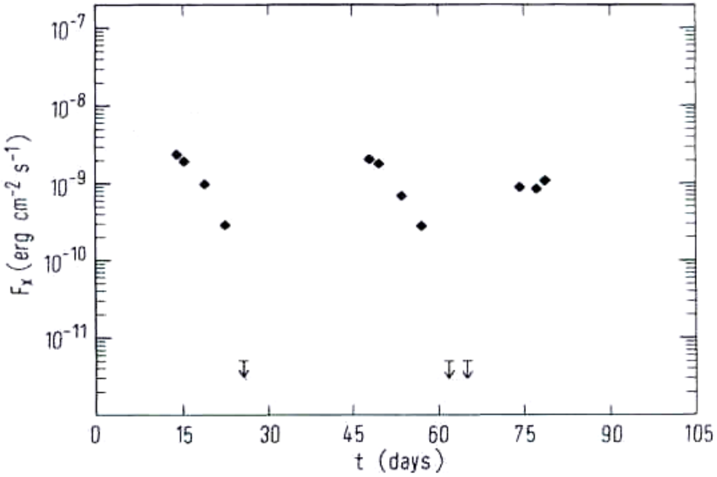
Very sharp X-ray luminosity decrease close to outburst end

V0332+53

P=4.4 s, B_{cyc}~10^{12} G

L(min)~10^{35} erg/s

(Stella, White & Rosner 1986)

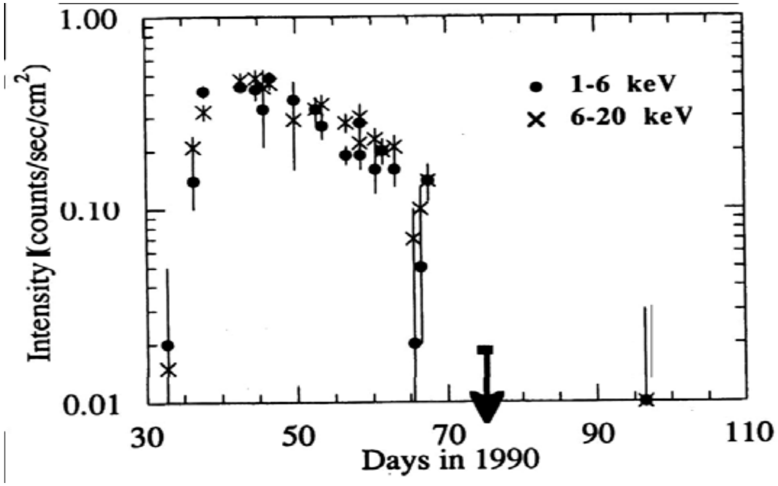


4U0115+63

P=3.6 s, B_{cyc}~10^{12} G

L(min)~10^{36} erg/s

(Tamura et al. 1992)



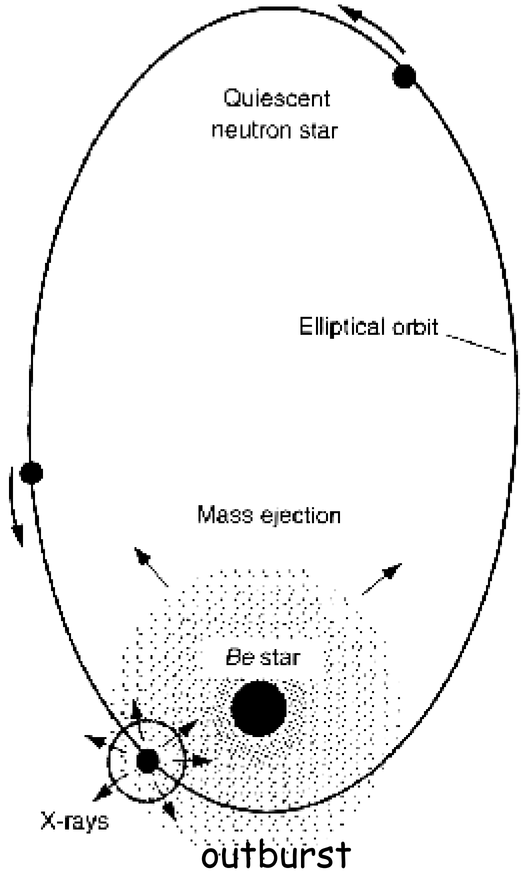
(see also Cui et al. 1995, 1998)

Different regimes in Hard XRTs

(X-ray pulsar/ Be star binaries)

(Stella, White & Rosner 1986)

- Centrifugal barrier likely closes close to an outburst end: X-ray flux decay should steepen suddenly
- Self-consistency check of interpretation, if P(spin), B and distance are measured

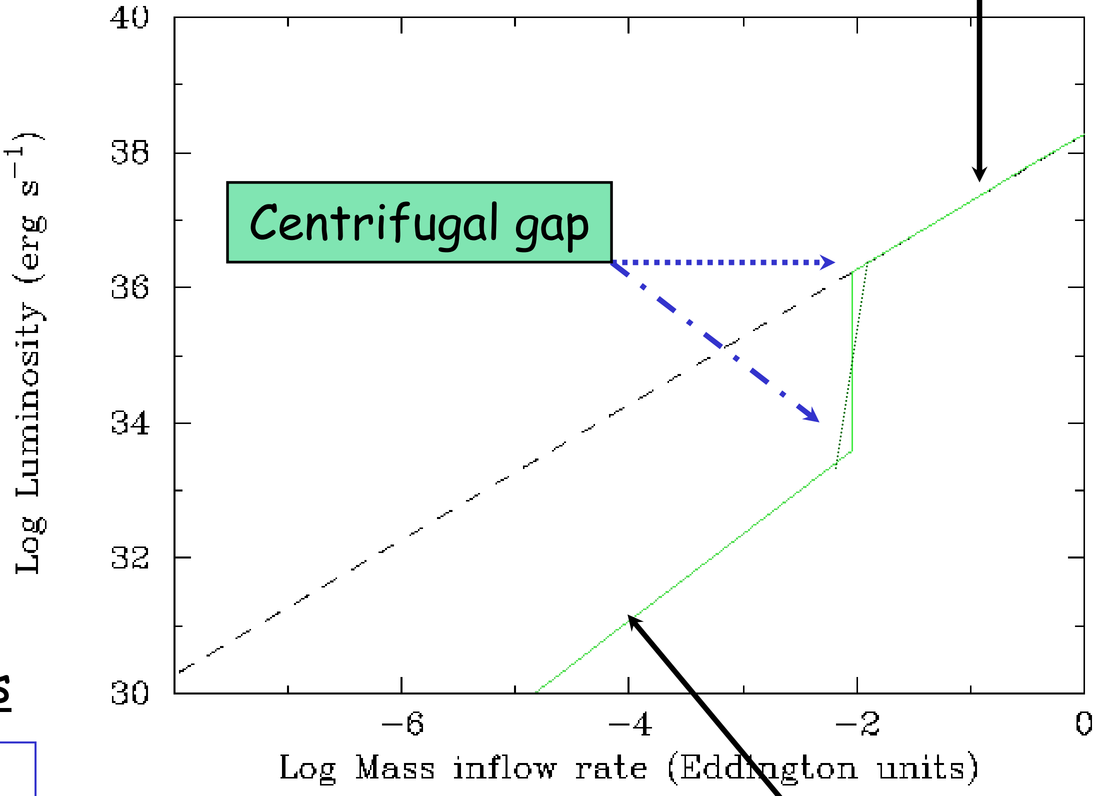


Expected mass-energy conversion efficiency in Hard XRTs

X-ray pulsar with $P\sim4$ s $B\sim10^{12}$ G

Accretion

L=GMM(dot)/R



Centrifugal gap

Propeller

L=GMM(dot)/r_m
$\propto M^{9/7}$

Centrifugal gap expectations

- factor of ~400 jump in Lx
- very steep dependence on M(dot) (not step-like !)

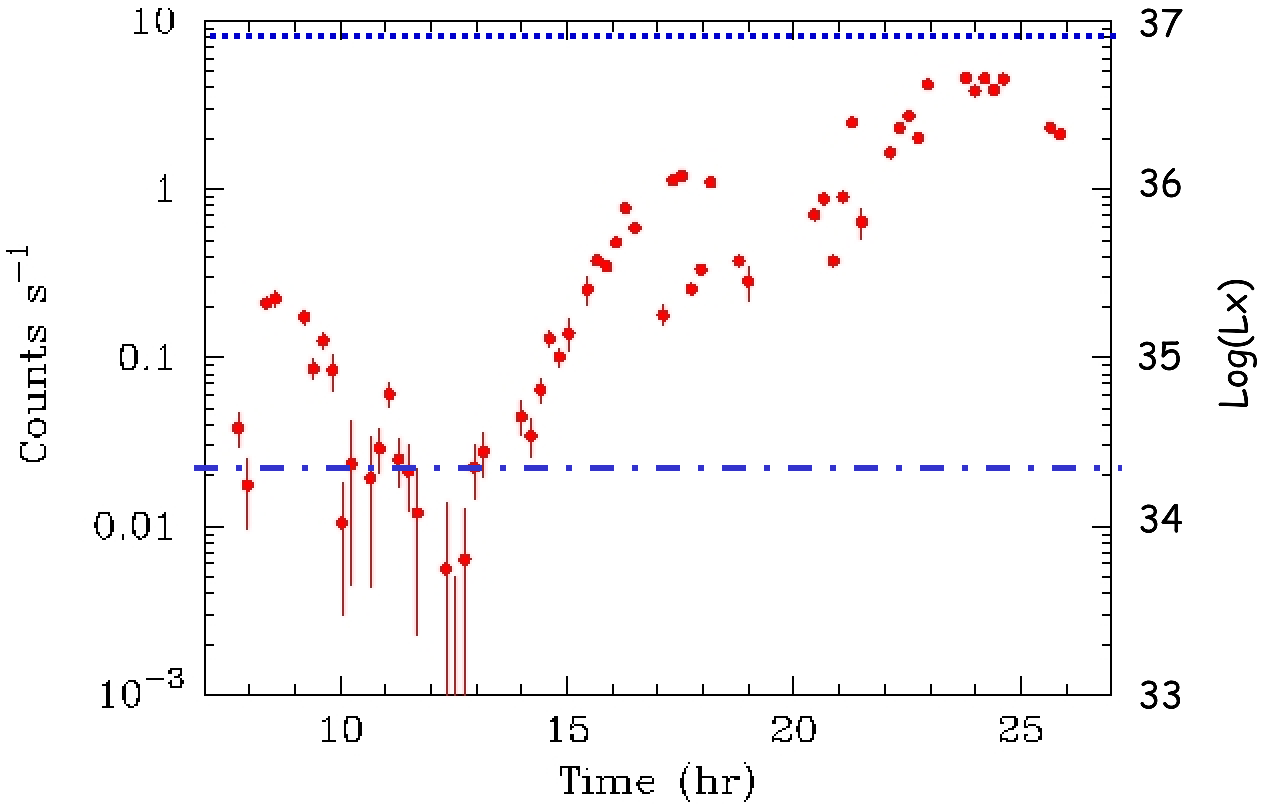
(Stella et al. 1994; Corbet 1995, Campana et al 1998)

BeppoSAX observation 4U0115+63 in quiescence

(Campana et al. 2001)

Expected range of centrifugal gap,
based on measured P, B and distance

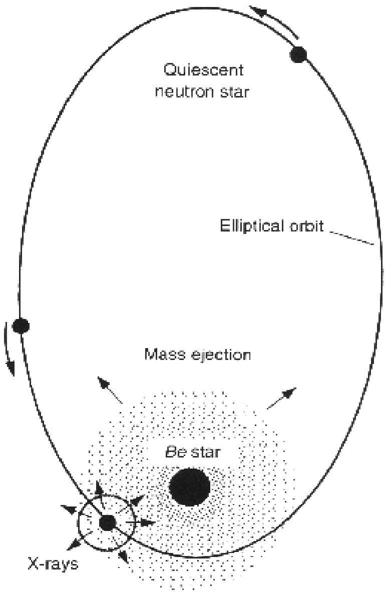
- Observed Lx within centrifugal gap !
- Very Large (factor of ~250) Lx variations!
- 3.6 s pulsations present
- No substantial pulsation amplitude and spectral variations



- Factor of < 3 variations in M(dot) expected at the most: imply a very steep dependence of Lx on M(dot) (power law slope of > 5)
- In the centrifugal gap some matter must leak through the barrier and accrete onto the NS surface ⇒ First evidence for centrifugal gap !

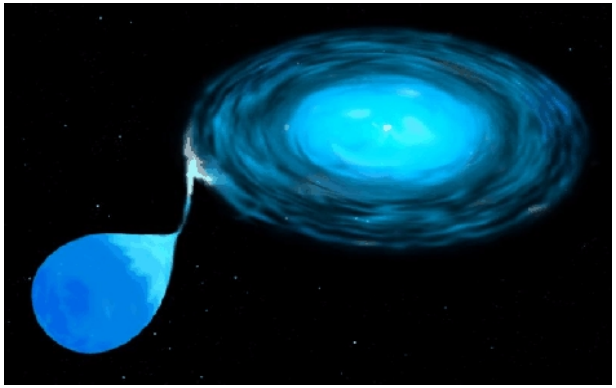
XRTs : spectral classification

Hard XRTs: young X-ray pulsating NSs in Be star binaries



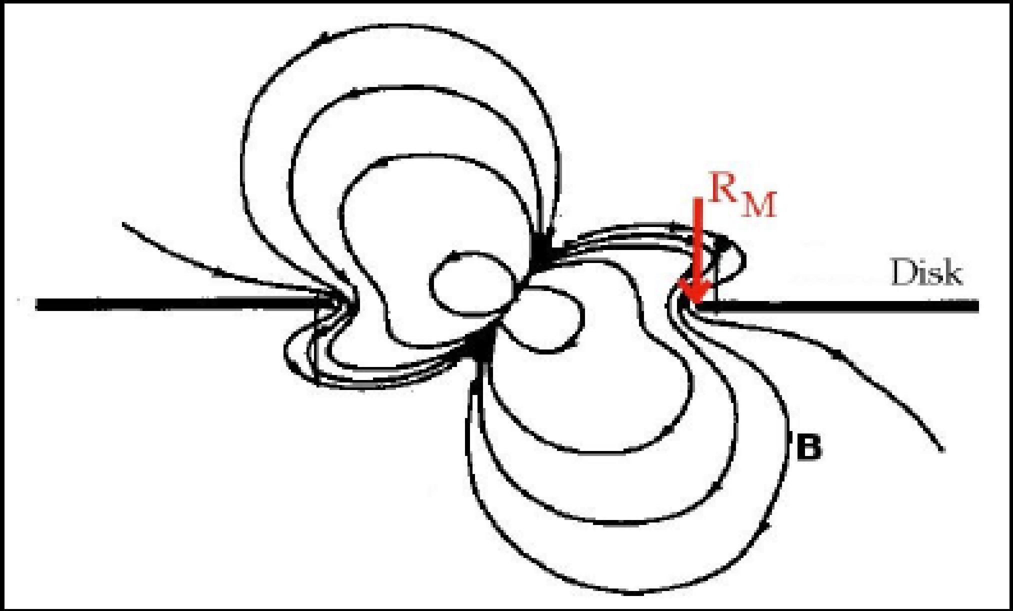
Soft XTRs: old (bursting) NSs in low mass X-ray binaries

(Ultra)-soft XTRs: black hole candidates in low mass X-ray binaries

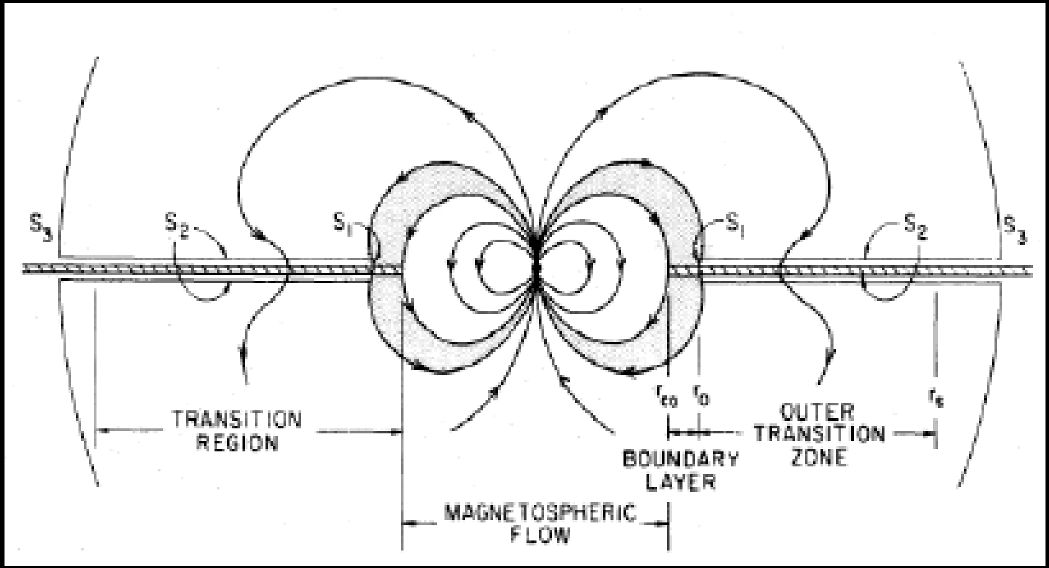


(White, Kaluzienski, Swank 1984)

Disk – Magnetosphere interaction

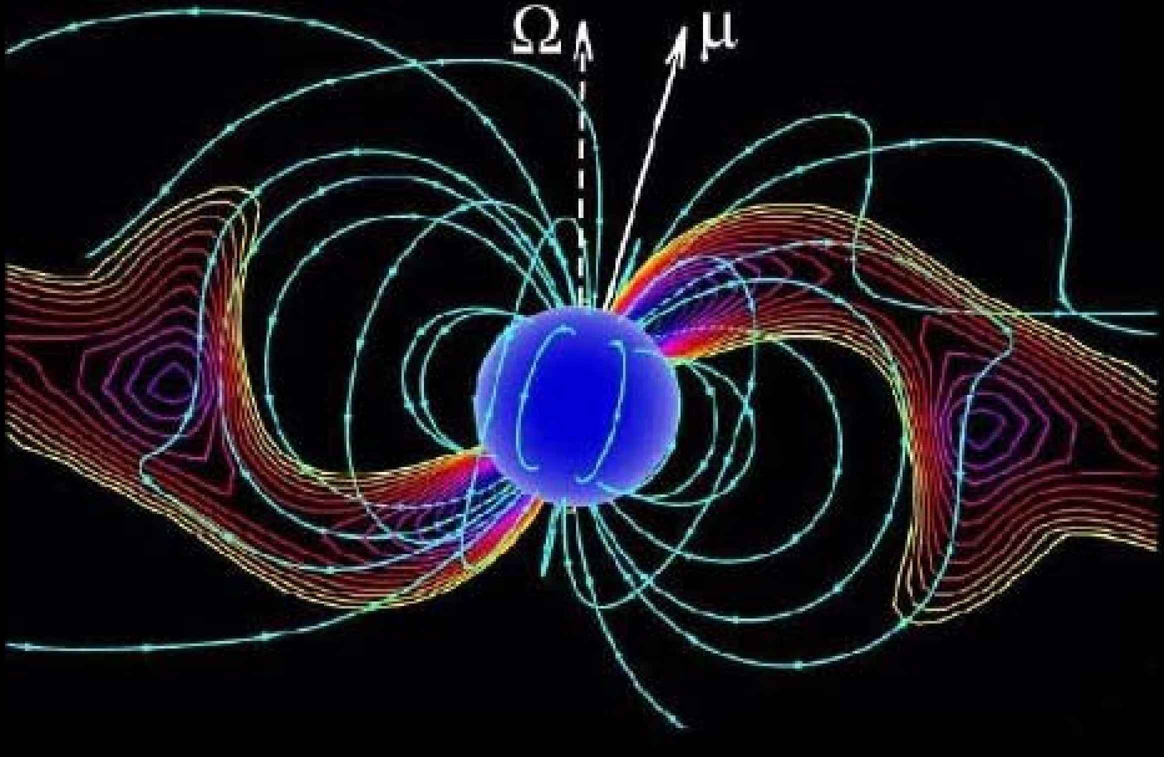


Diamagnetic disk model
(Aly, 1980)



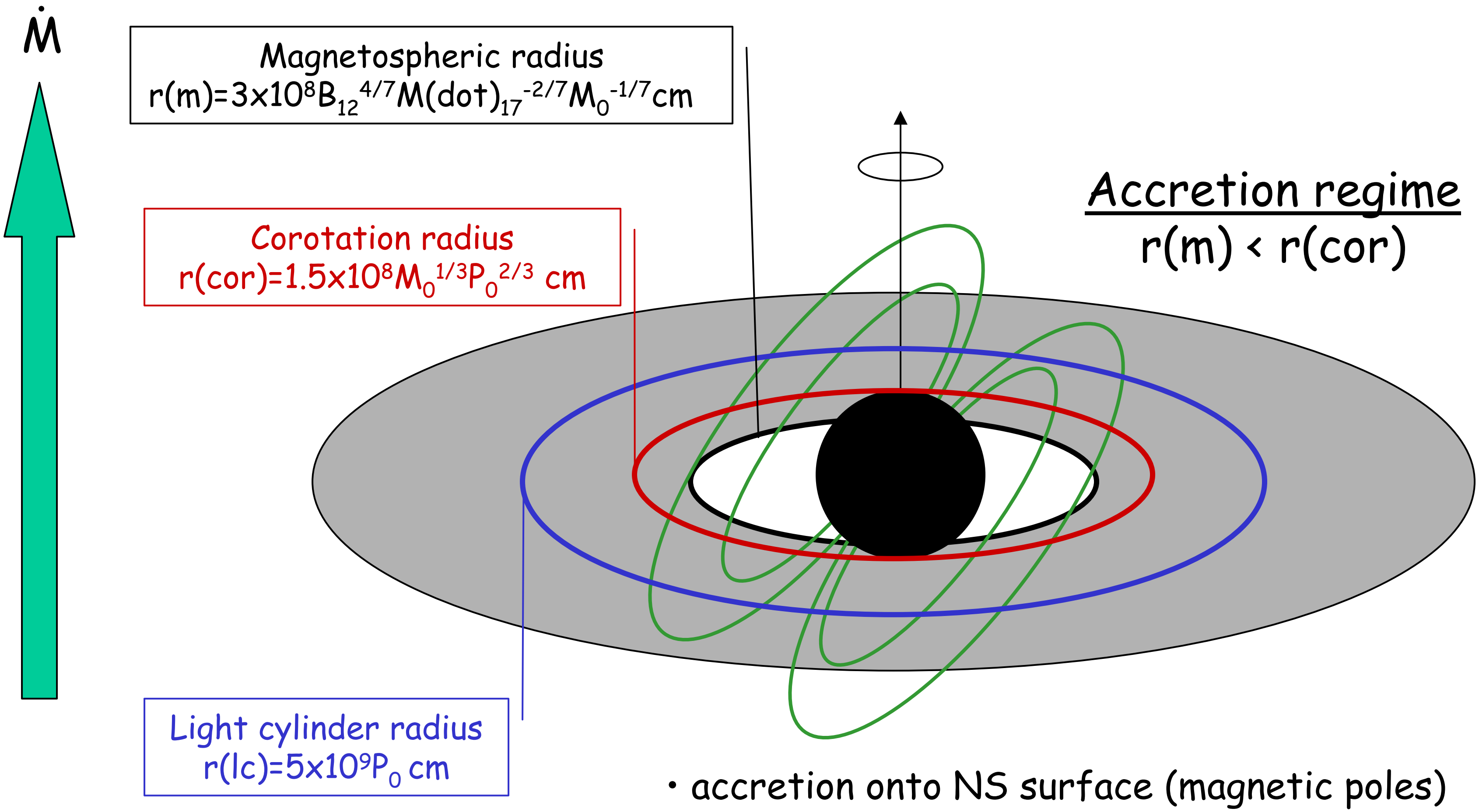
Magnetically threaded disk model
(Ghosh & Lamb, 1979)

Accretion onto an oblique rotator



Different regimes for a rotating magnetic NS: 1

(Illarionov & Sunyaev 1975)



$\dot{M}$

Magnetospheric radius
$r(m)=3x10^{8}B_{12}^{4/7}M(dot)_{17}^{-2/7}M_{0}^{-1/7}cm$

Corotation radius
$r(cor)=1.5x10^{8}M_{0}^{1/3}P_{0}^{2/3}$ cm

Light cylinder radius
$r(lc)=5x10^{9}P_{0}$ cm

Accretion regime

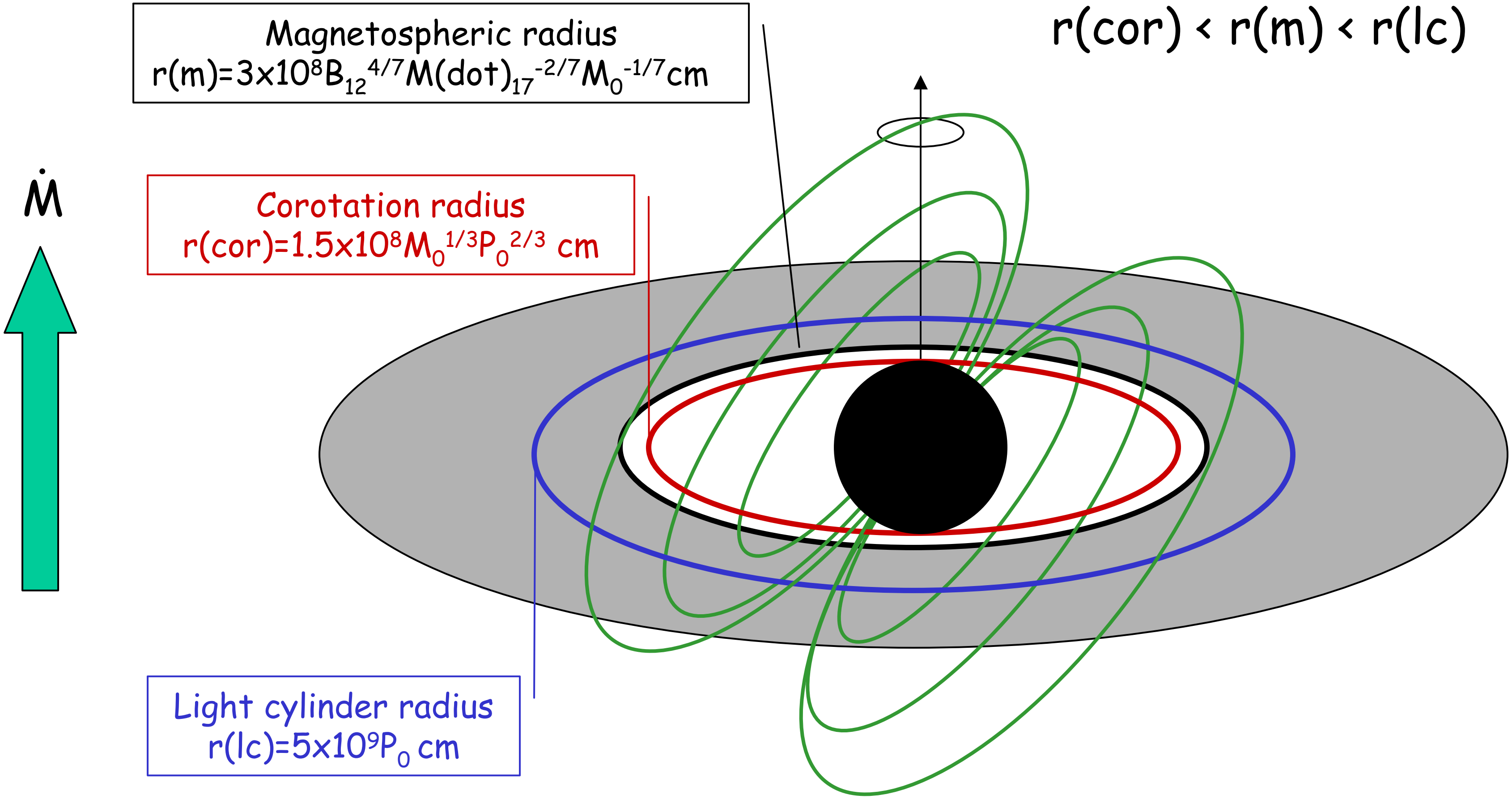
$r(m) < r(cor)$

- accretion onto NS surface (magnetic poles)
- energy release L=GMM(dot)/R*

Different regimes for a rotating magnetic NS: 2

Propeller regime

r(cor) < r(m) < r(lc)



Magnetospheric radius
$r(m)=3\times10^{8}B_{12}^{4/7}M(dot)_{17}^{-2/7}M_{0}^{-1/7}$cm

Corotation radius
$r(cor)=1.5\times10^{8}M_{0}^{1/3}P_{0}^{2/3}$ cm

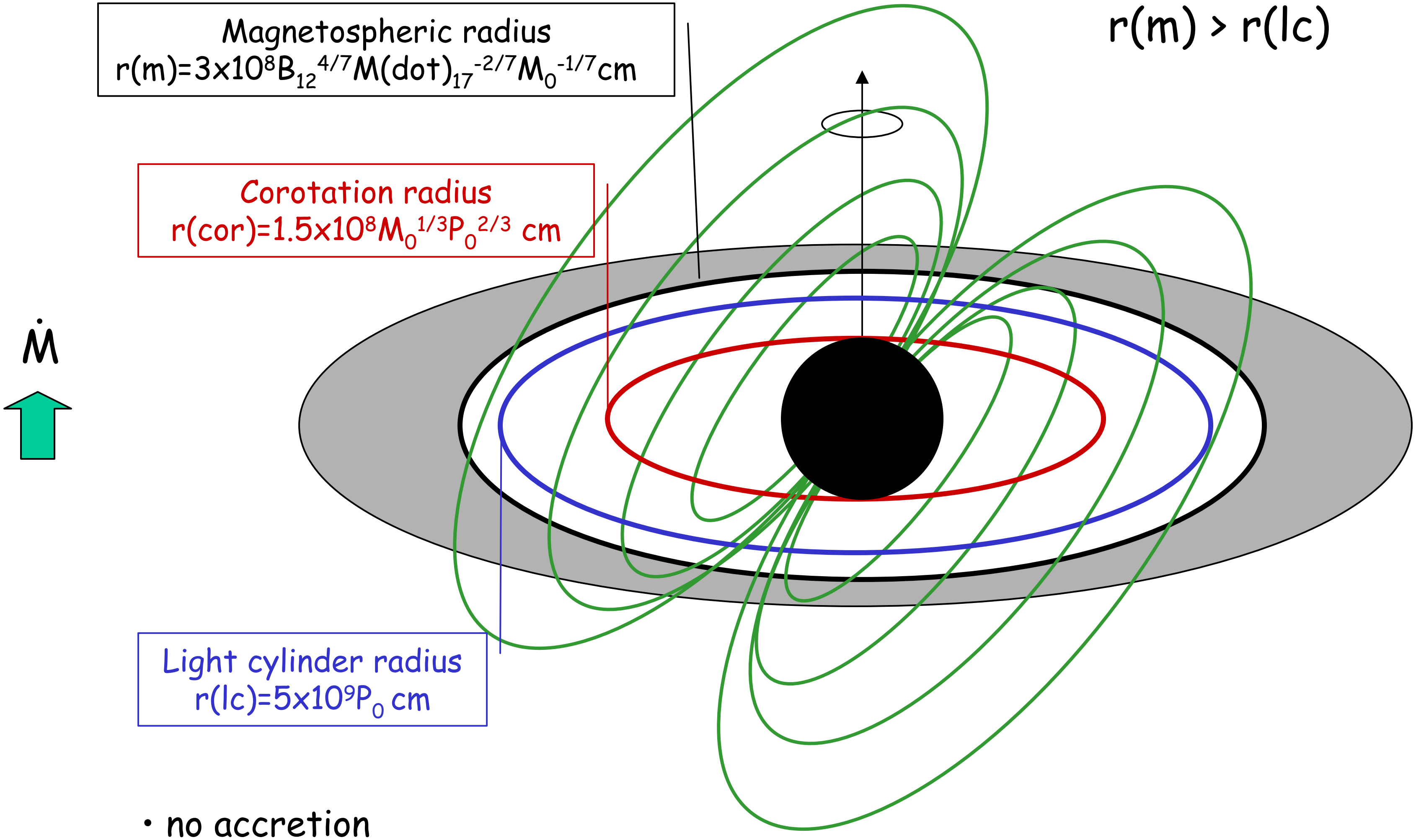
Light cylinder radius
$r(lc)=5\times10^{9}P_{0}$ cm

- centrifugal barrier closes (B-field drag stronger than gravity)
- matter accumulates or is ejected from r(m)
- accretion onto r(m): lower gravitational energy released

Different regimes for a rotating magnetic NS: 3

Radio Pulsar regime

$r(m) > r(lc)$



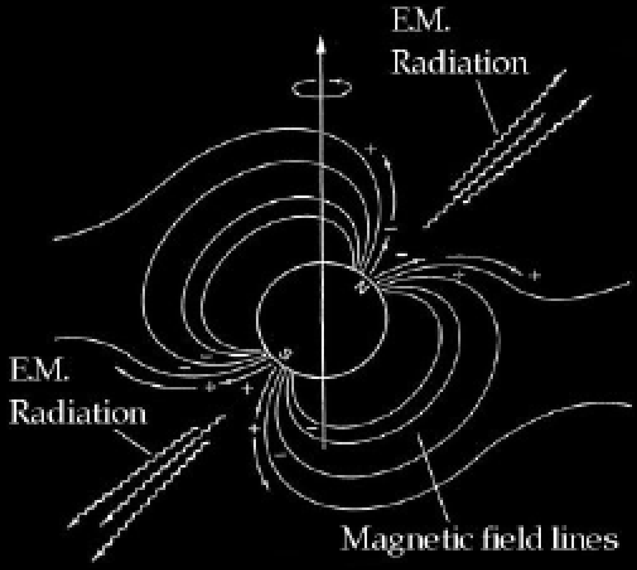
Magnetospheric radius
$r(m)=3\times10^{8}B_{12}^{4/7}M(dot)_{17}^{-2/7}M_{0}^{-1/7}$cm

Corotation radius
$r(cor)=1.5\times10^{8}M_{0}^{1/3}P_{0}^{2/3}$ cm

Light cylinder radius
$r(lc)=5\times10^{9}P_{0}$ cm

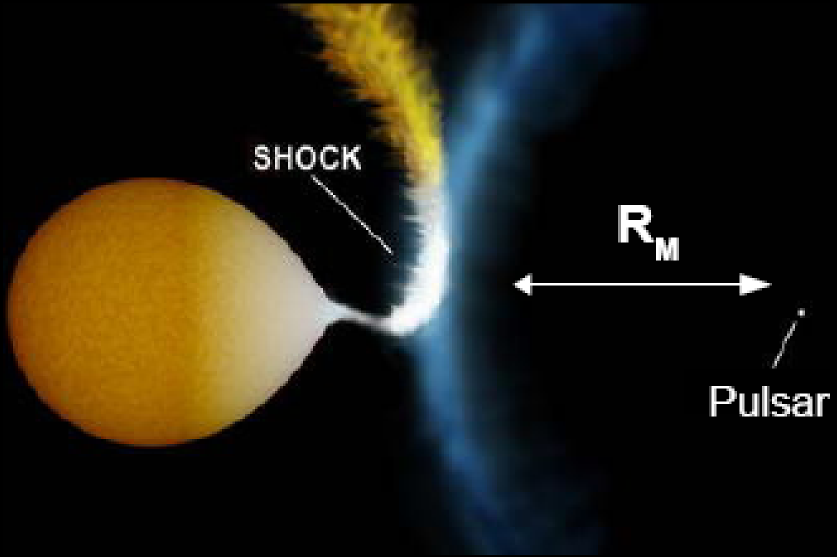
- no accretion
- disk matter swept away by pulsar wind and pressure

The Light Cilinder Radius

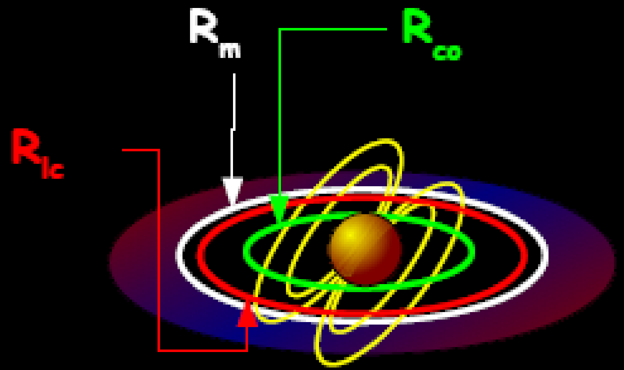


$$R_{lc}\,\Omega_{spin} = c$$

Radiation Pressure may prevent the disk formation or destroy a previously present accretion disk



$$R_M \geq R_{cl}$$ “Radio Pulsar” regime

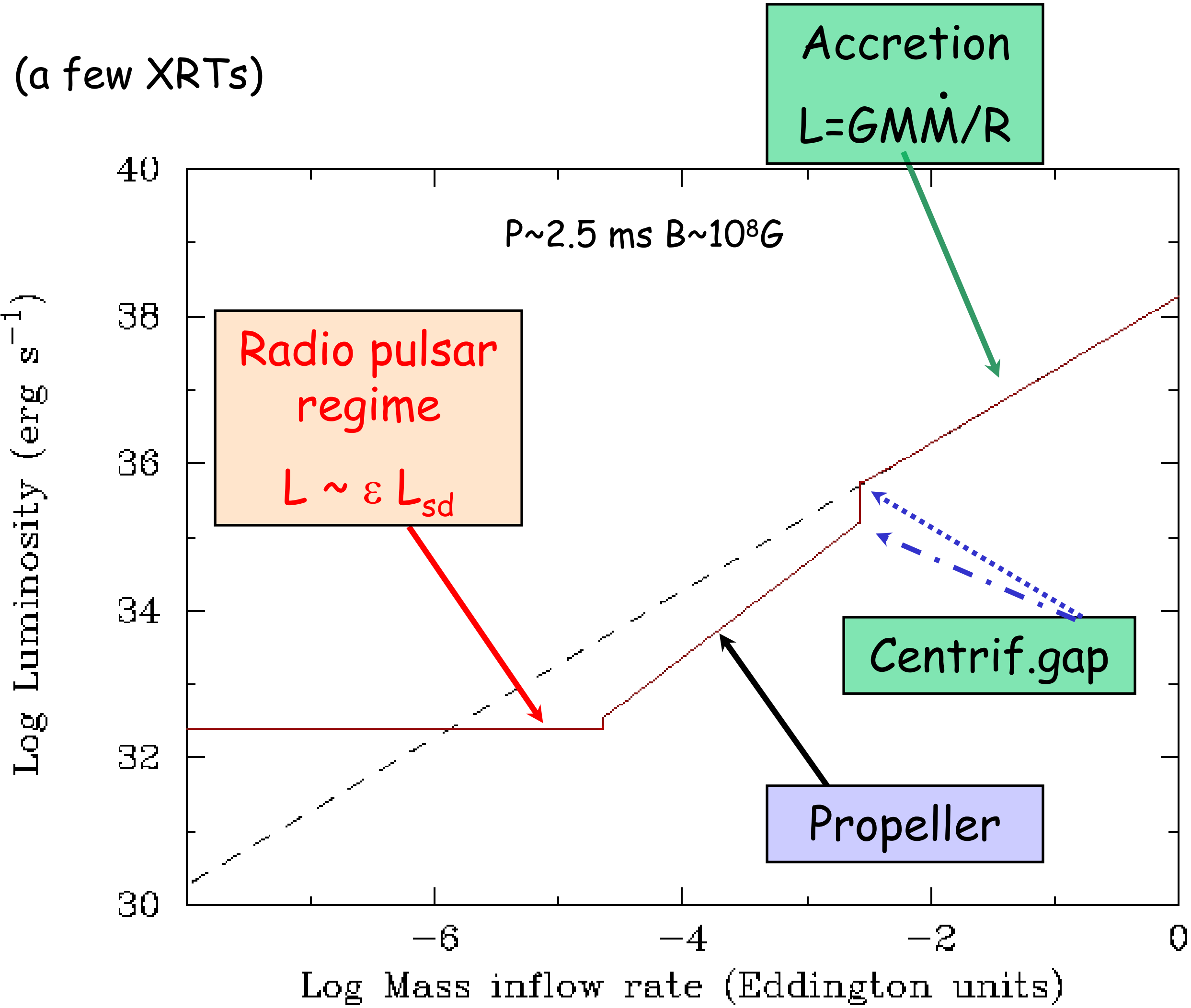


Expected mass-energy conversion efficiency in Soft XRTs

P~ 1.6-4 ms in ~20 LMXRBs (a few XRTs)

Basic expectations

- small centrifugal gap
- propeller regime over a range of ~100 in dM/dt
- radio pulsar regime for very low mass inflow rates: shock emission



Accretion

$L=GM\dot{M}/R$

Radio pulsar regime

$L \sim \varepsilon L_{sd}$

Centrif.gap

Propeller

(Stella et al. 1994, Campana et al .1998)

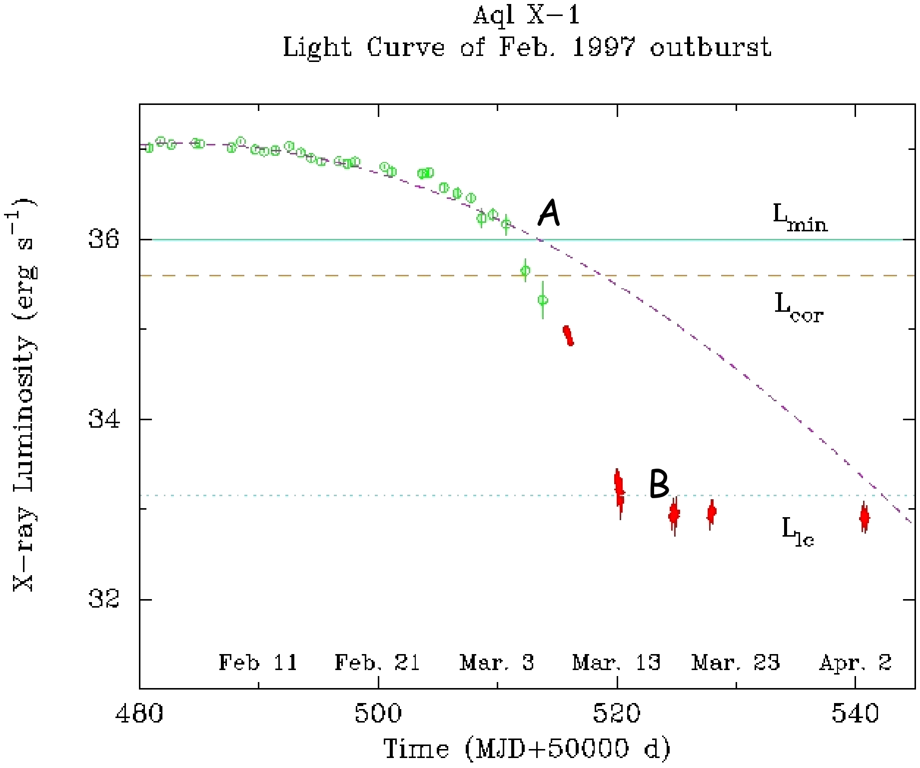
Soft XRTs: Aql X-1 from outburst to quiescence

Two transitions observed in outburst decay:

A - Lx~ 10^{36} erg/s, decay ~ 1 d,
spectrum hardens

B - Lx~ 10^{33} erg/s, levels off,
power law component
decreases and flattens

P = 1.8 ms during bursts



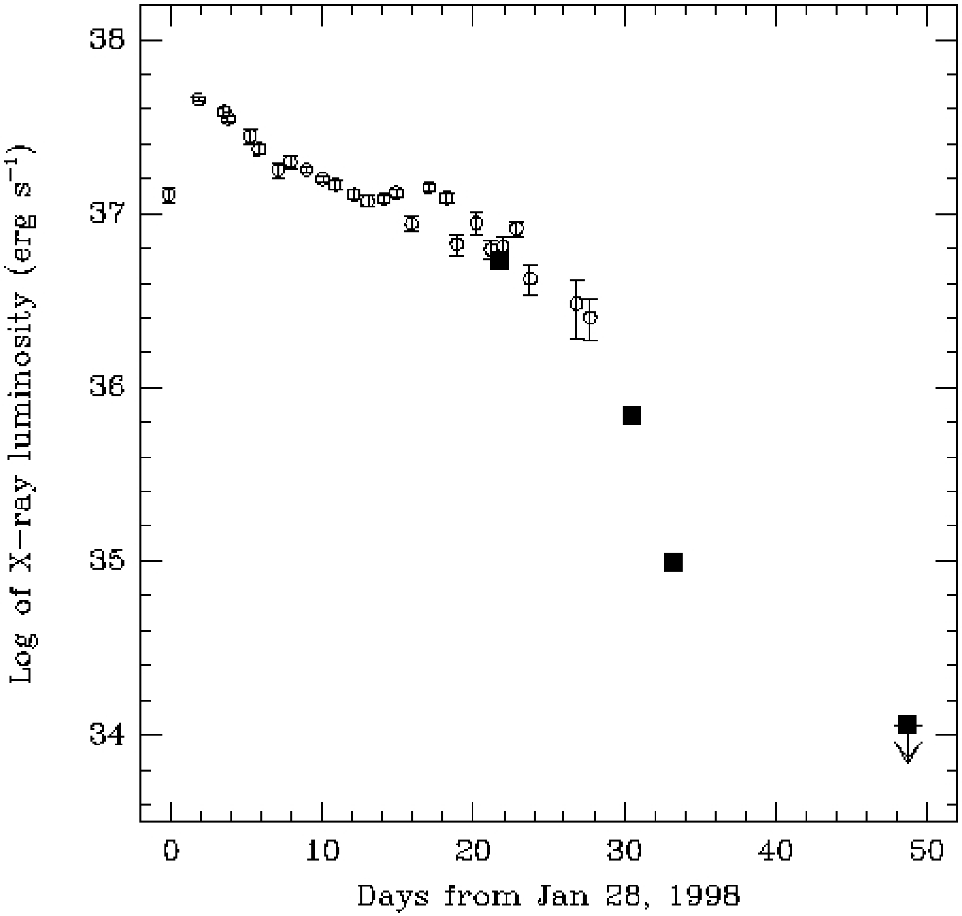
Aql X−1
Light Curve of Feb. 1997 outburst

(Campana et al. 1998)

Soft XRTs: steepening of outburst decay

Decay steepens at
Lx~ 2×10^{36} erg/s

The Rapid Burster 4U1730-33



(Masetti et al. 2000)

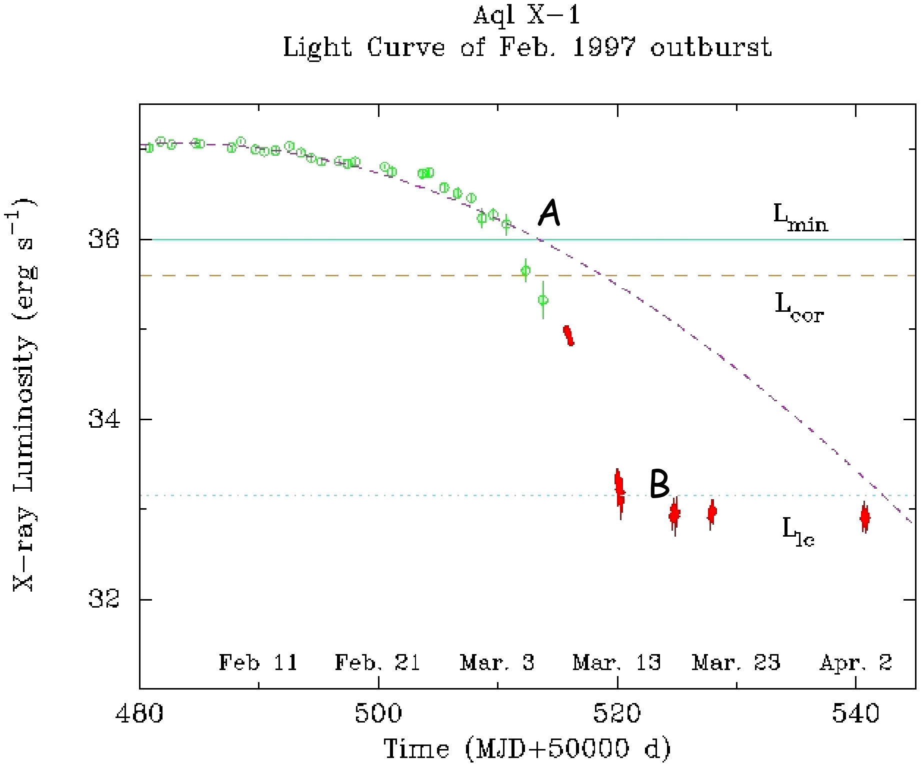
Soft XRTs: Aql X-1 from outburst to quiescence

Two transitions observed in outburst decay:

A - Lx~ 10^{36} erg/s, decay ~ 1 d,
spectrum hardens

B - Lx~ 10^{33} erg/s, levels off,
power law component
decreases and flattens

P = 1.8 ms during bursts



(Campana et al. 1998, Zhang et al. 1998)

Interpretation

A - Onset of centrifugal barrier, then propeller: requires B-field ~ 1-3 x 10^{8} G

Soft XRTs: Aql X-1 from outburst to quiescence

Two transitions observed in outburst decay:

A - Lx~ 10^{36} erg/s, decay ~ 1 d,
spectrum hardens

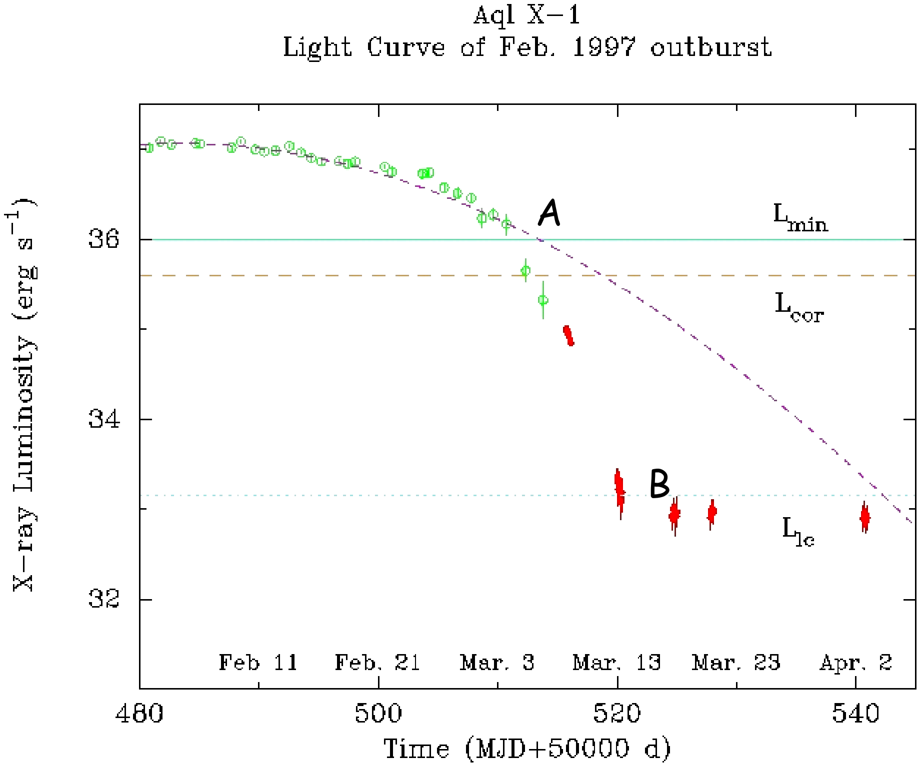
B - Lx~ 10^{33} erg/s, levels off,
power law component
decreases and flattens

Interpretation

A - Onset of centrifugal barrier, then propeller: requires B-field ~ 1-3 x 10^8 G

B - Transition to the radio pulsar regime; quiescent emission by shock emission: requires
$L \sim \varepsilon L_{sd}$ $L \sim (0.1\text{-}0.01) L_{sd}$;
extended power law spectrum expected

P = 1.8 ms during bursts



(Campana et al. 1998, Zhang et al. 1998)

SAX J1808.4-3658

Soft XRT: type I bursts, 2.5 ms coherent pulsations in pers. emission

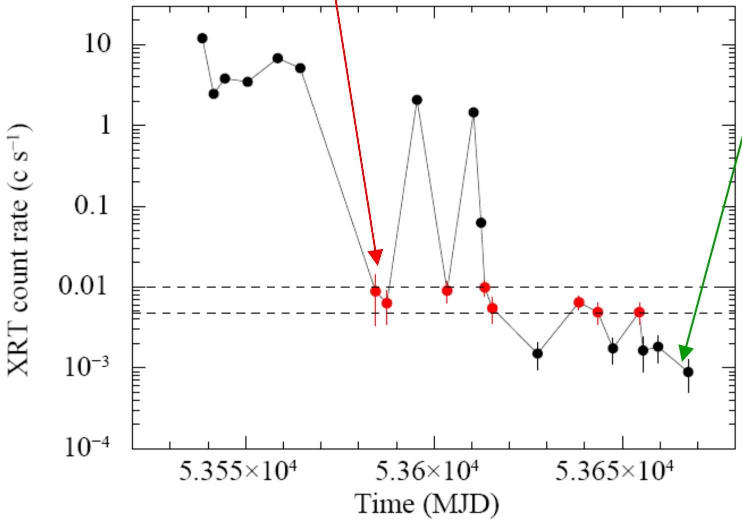
Porb ~ 2hr (in't Zand et al. 1998, Wijnands & van der Klis 1998, Chakrabarty & Morgan 1998)

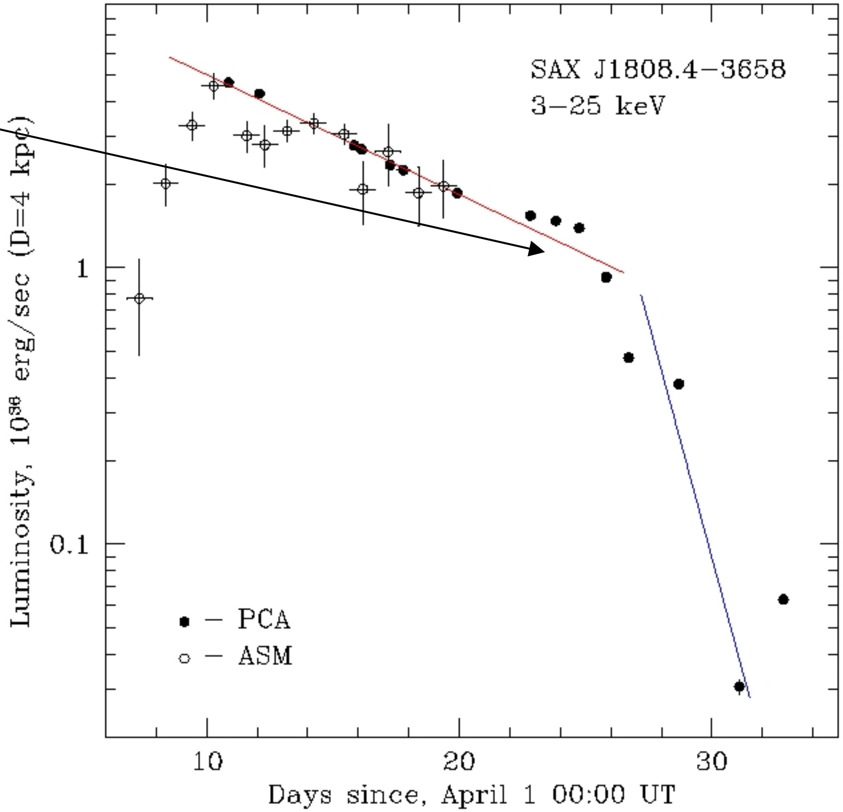
⇨ Direct evidence for a magnetosphere: B~ 10^8 -10^9 G (Psaltis & Chakrabarty 1998)

"knee" at 10^{36} erg/s: onset of propeller

Metastable state at 5x10^{32} erg/s: end of propeller ?

Quiescent state at 5x10^{31} erg/s: radio pulsar regime ?





(Gilfanov et al. 1998; Rappaport et al 2003, Chakrabarti et al 2004, Campana et al 2008)

In the propeller regime

Observations:

Quiescent X-ray pulsar binaries

- Only a few cases studied (4U0115+63, A0538-66, V0332+53)
- Measured luminosities (Lx ~ $10^{33\text{-}35}$ ergs/s) consistent with propeller regime

Cataclysmis Variables

- AE Aqr: propeller/ejector at ~ r(circularisation)

Theory

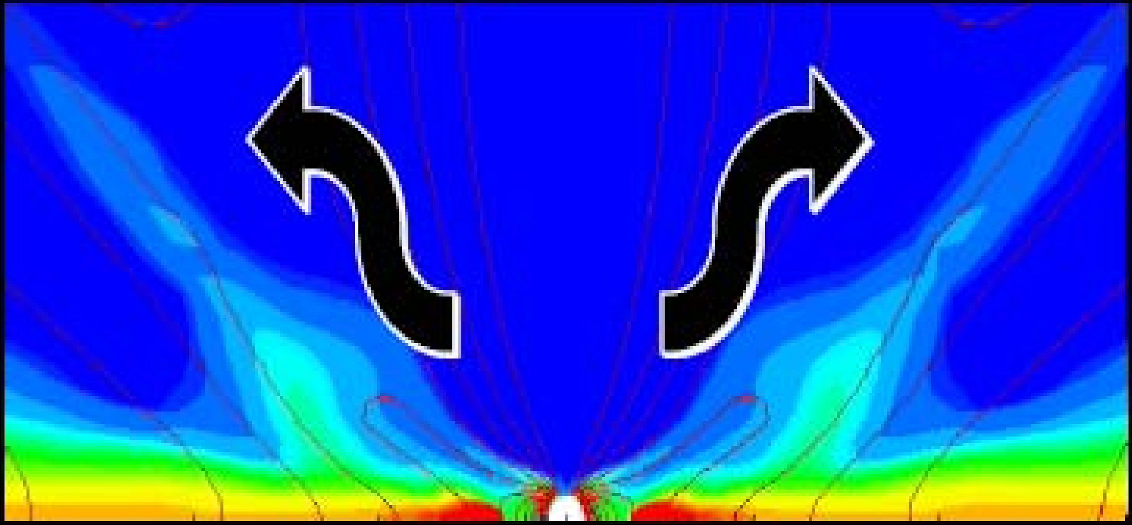
- Basic issue: the fate of matter that cannot penetrate the magnetosphere
  - Ejection to infinity ?
  - Accumulation and release ?

- Models:
  - Quasi steady "atmosphere" at R(m) (Davies & Pringle 1981)
  - Ejector/flywheel models (Wang & Robertson 1985; Priedhorsky 1986; Minesighe, Rees &Fabian 1991)
  - Very high energy particles and gamma-rays produced ? (Mejnties & de Jager 2000)
  - Mass storage and release instability at R(m) (Baan 1977, 1978; Spruit & Taam 1993)

The Corotation Radius

$$\Omega_{.} = \frac{۲\pi}{P_{spin}} = \Omega_k(R) = (\frac{GM}{R^{۳}}) \Rightarrow \qquad R_{cor} = ۱.۵ \times ۱۰^{۸} (\frac{M}{M_{sun}})^{۱/۳} (\frac{P_{spin}}{۱\,sec})^{۲/۳}\ cm$$

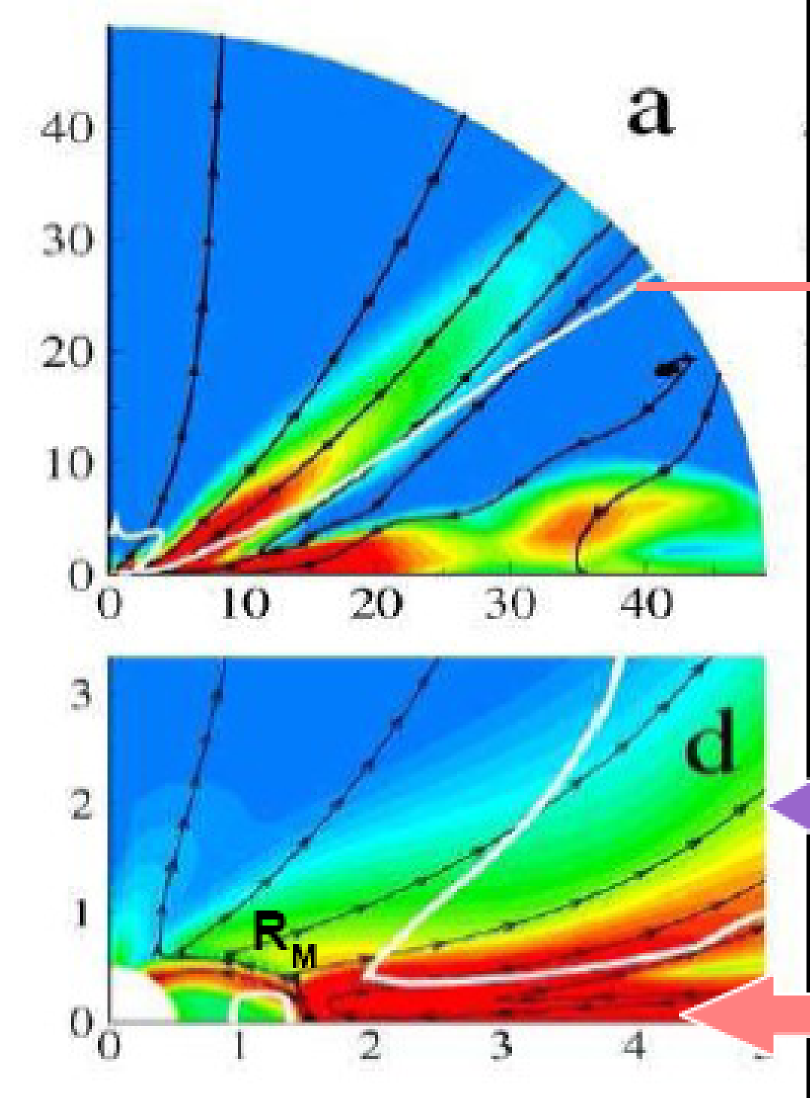
The Propeller effect (Illarionov & Sunyaev, 1975): ejection of matter



(Romanova et al., 2005)

$R_M \geqslant R_{co}$ The "**Propeller**" regime

MHD SIMULATIONS of Propeller Regime of Disk Accretion to Rapidly Rotating Stars (Ustyugova et al., 2006)



MATTER OUTFLOWS FROM THE CORONA ABOVE THE DISK

(a) Simulation Region

$V=V_{esc}$

(b) Inner simulation region

Outflow from the corona

Mass Inflow from the central disk

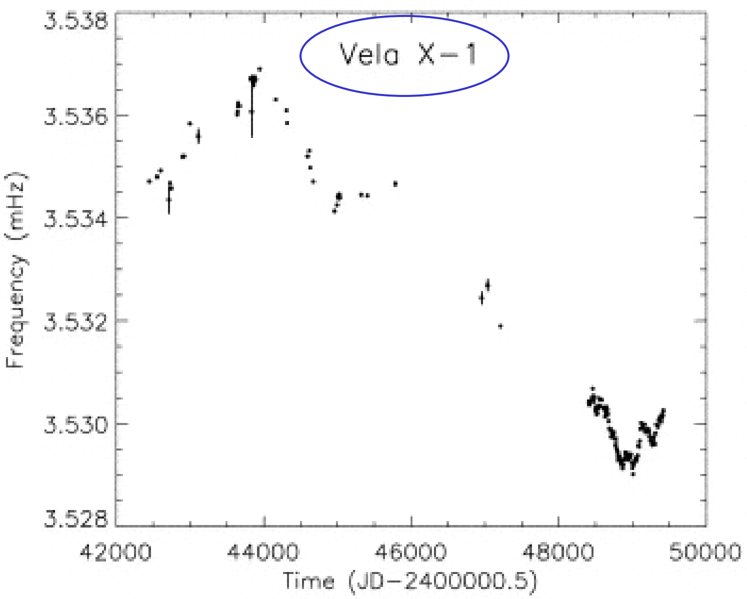
Accretion torques: basics

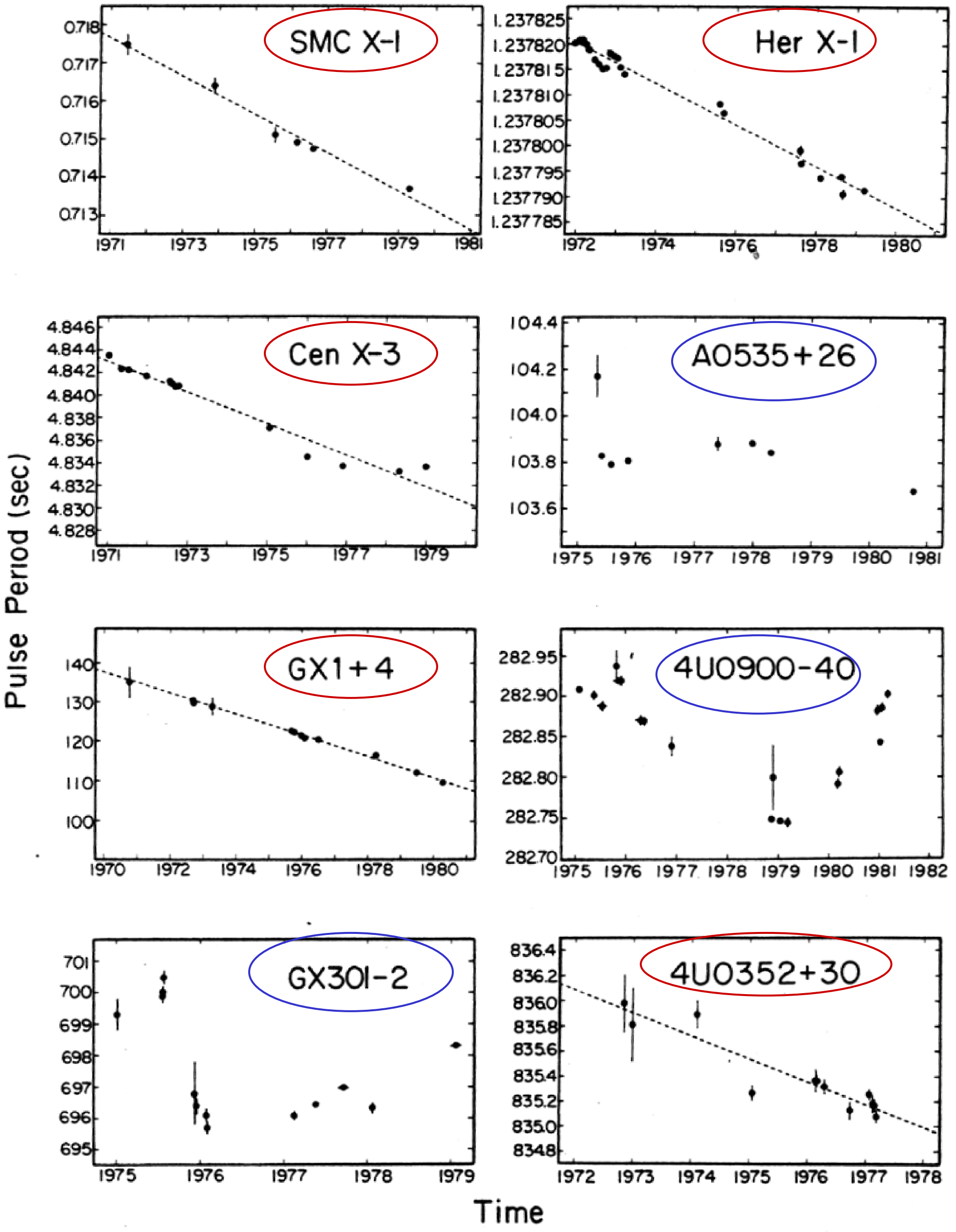
- Disk-Accreting Neutron stars in X-ray Binaries

  Positive Torques -> Spin-Up

- Wind-Accreting Neutron stars in X-ray binaries

  Accretion torques of varying sign -> alternating spin up/down





Accretion disk/magnetosphere torques

$$\frac{d}{dt}(I\Omega) = \dot{M}\; l(r(m)) - \alpha$$

Non-material torques

Material torques

Corotation radius
$r(cor)=1.5\times10^{8}M_{0}^{1/3}P_{0}^{2/3}$ cm

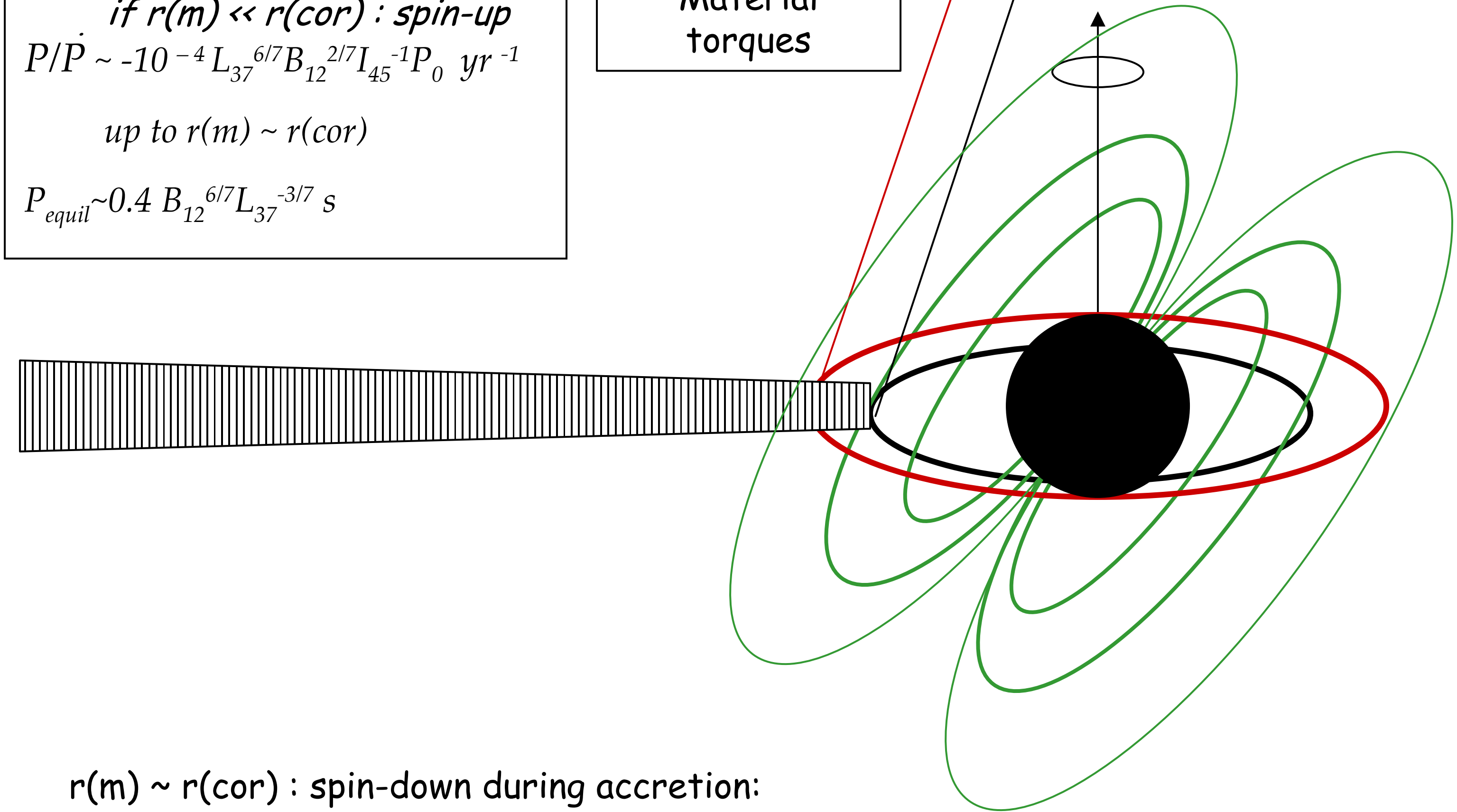
Magnetospheric radius
$r(m)=3\times10^{8}B_{12}^{4/7}\dot{M}_{17}^{-2/7}M_{0}^{-1/7}$cm

if r(m) << r(cor) : spin-up

$$P/\dot{P} \sim -10^{-4} L_{37}^{6/7} B_{12}^{2/7} I_{45}^{-1} P_{0}\; yr^{-1}$$

up to r(m) ~ r(cor)

$$P_{equil} \sim 0.4\, B_{12}^{6/7} L_{37}^{-3/7}\ s$$



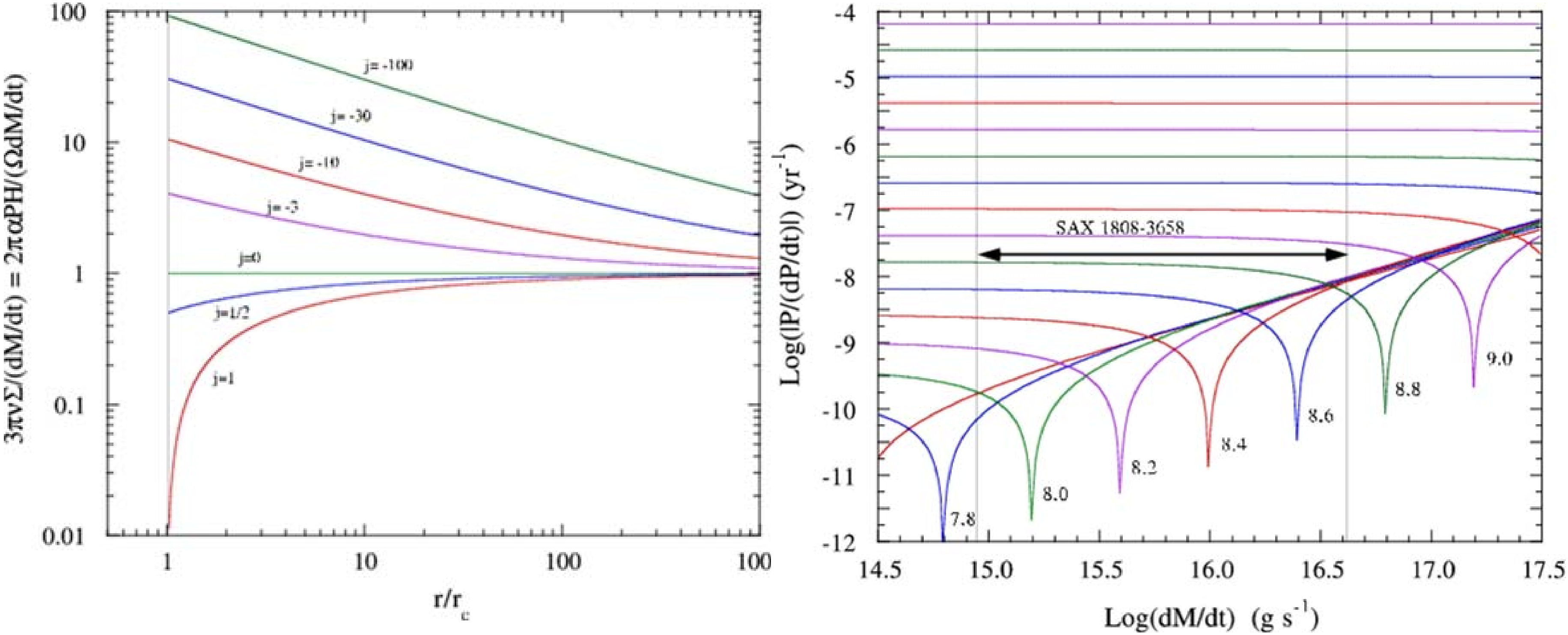
r(m) ~ r(cor) : spin-down during accretion:

-Non material torques: threading B-field / disk interaction (Ghosh & Lamb 1979);
gravitational waves (Bildsten 1998; Cutler et al 1999)

-Angular momentum carried outwards by the disk (Popham & Narayan 1991, Spruit & Taam 1993) or disk extending to R(cor) (Rappaport et al. 2003)

Spin-down during accretion

-Example: disk extending to R(cor) (Rappaport et al. 2003)



Torques evolve with continuity from positive to negative: stability expected at P_{equil}

But: some observations contradict this basic expectation !

The case of GX1+4 and 4U1626-67

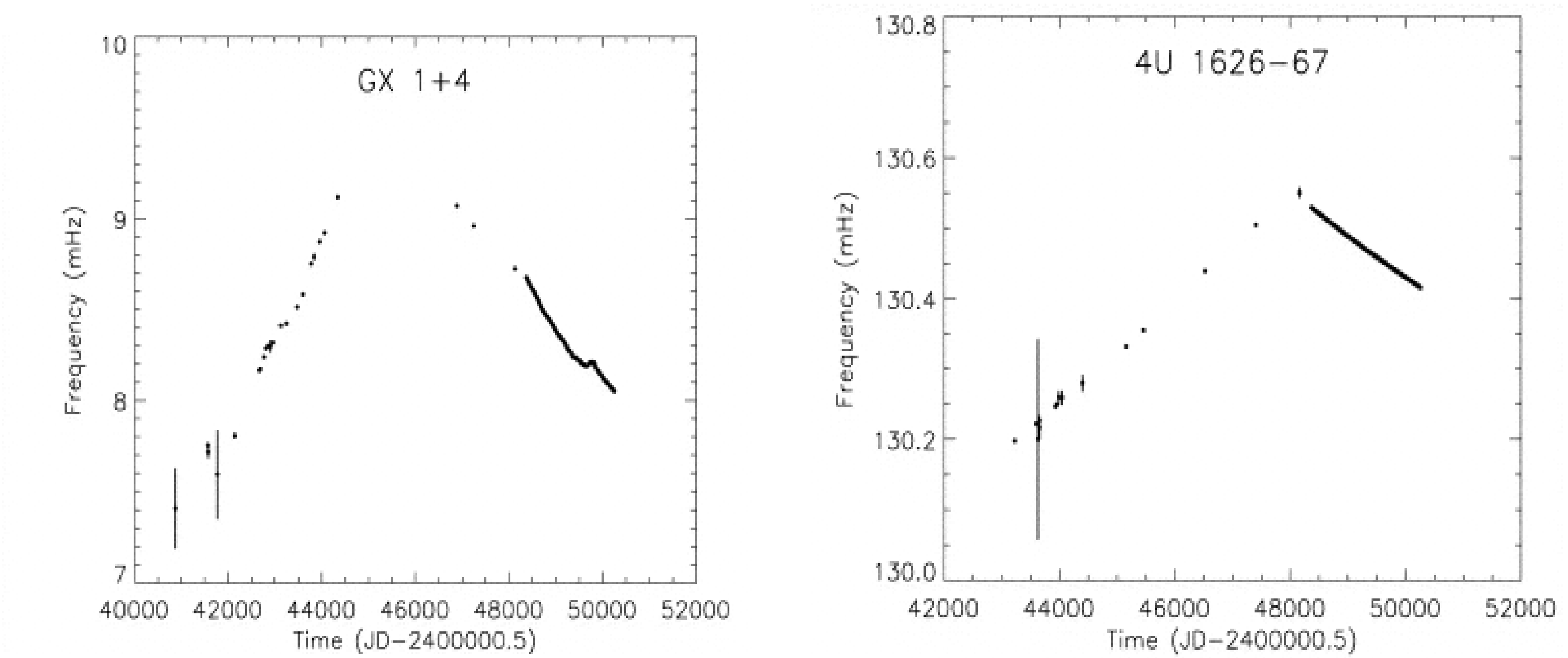
~ 100 s pulsar with M6 giant companion

-Spin-up timescale of ~100 yr

-Then … spin-down timescale of ~ 100 yr

- Lx stays nearly constant

~7 s pulsar
~1 hr binary
-Very low mass companion
-Lx stays nearly constant

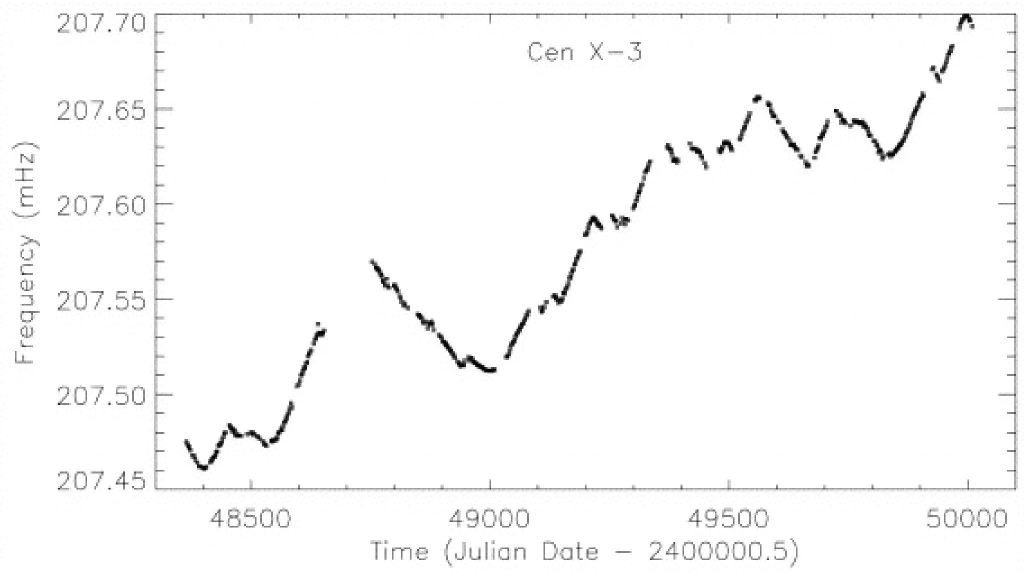


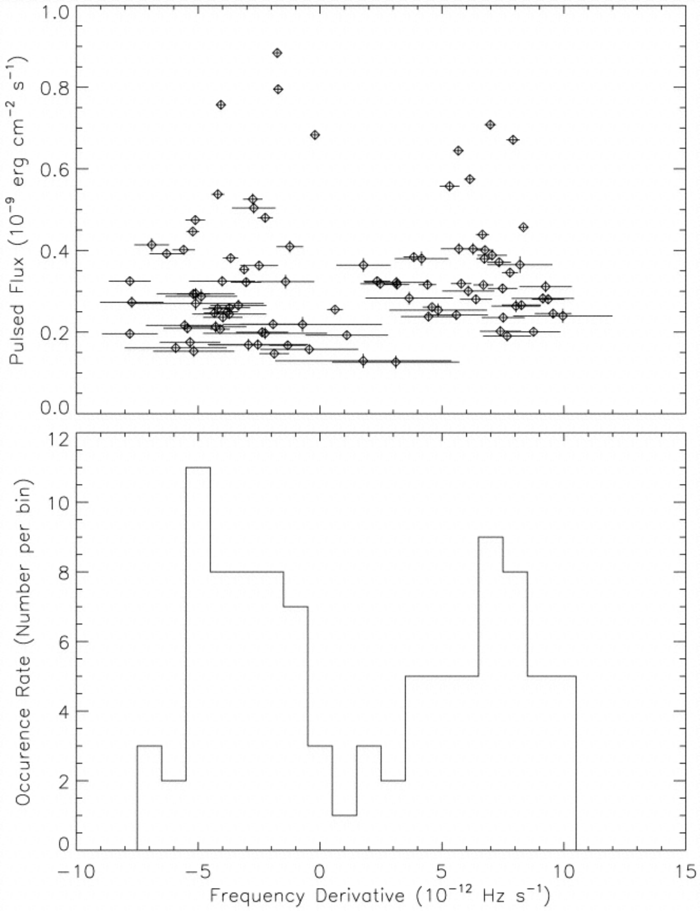
(Bildsten et al. 1997)

Cen X-3

(Bildsten et al. 1997)

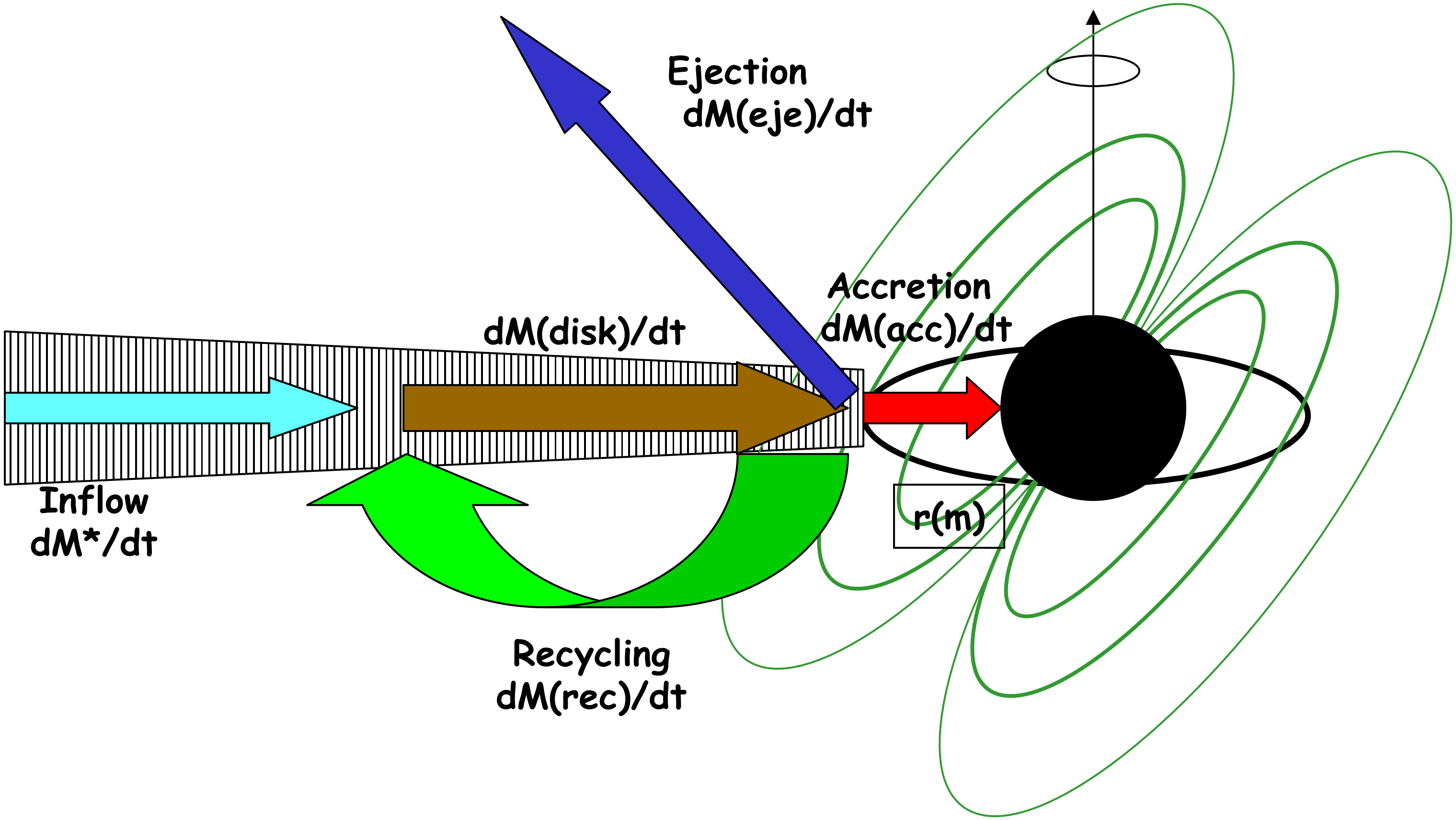
- •Prototypical disk-accreting eclipsing X-ray pulsar with supergiant companion
- •P(spin) ~ 4.4 s
- • Bimodal distribution of P(dot)





The “recycling” magnetosphere

Basic ansatz: it can sustain in general:
accretion, ejection and recycling

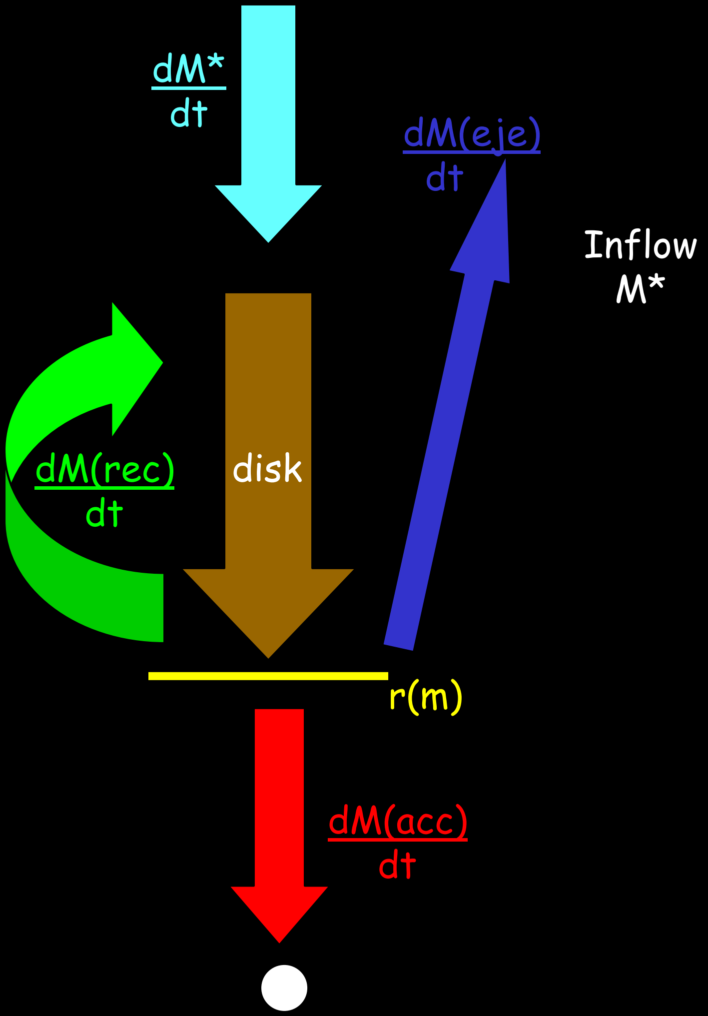


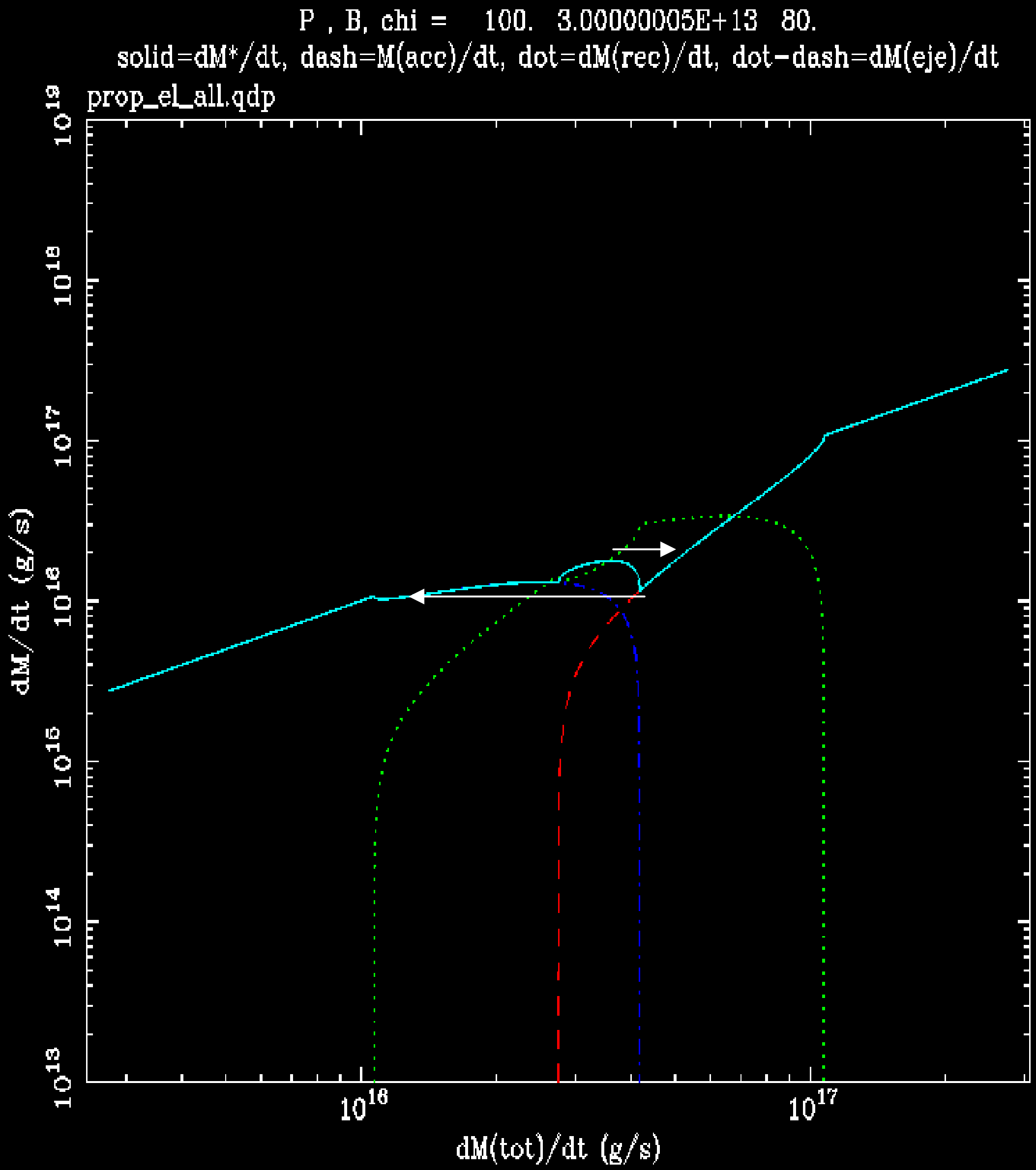
- **Steady state solutions must have dM*/dt = dM(acc)/dt + dM(eje)**
- **r(m) determined by dM(disk)/dt = dM*/dt + dM(rec)/dt**

Are there multiple solutions for a given mass in flow rate dM*/dt ?

(Perna et al. 2006)

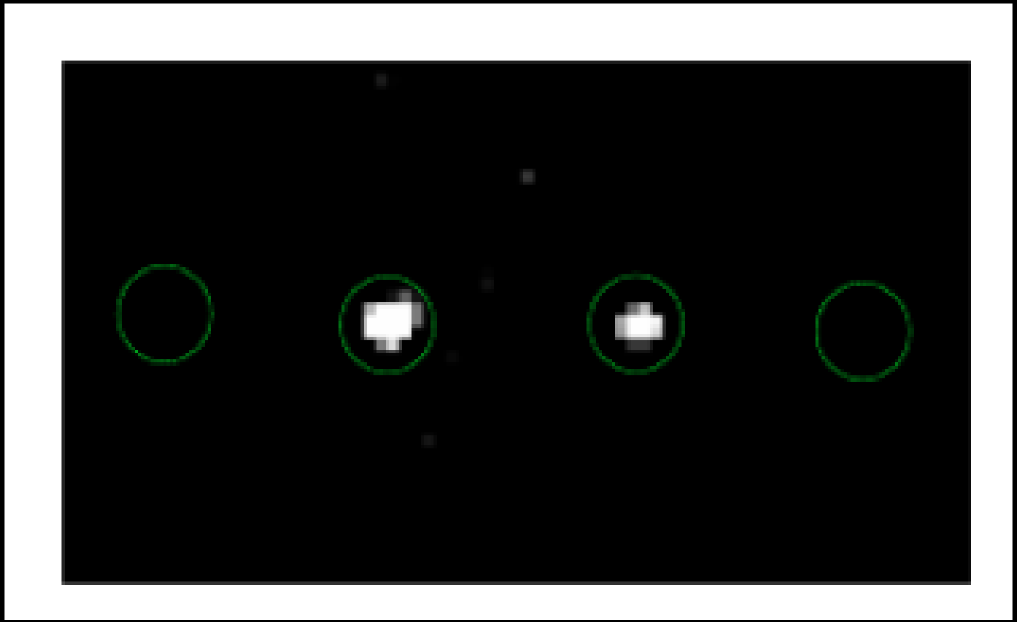
Parameters for GX1+4

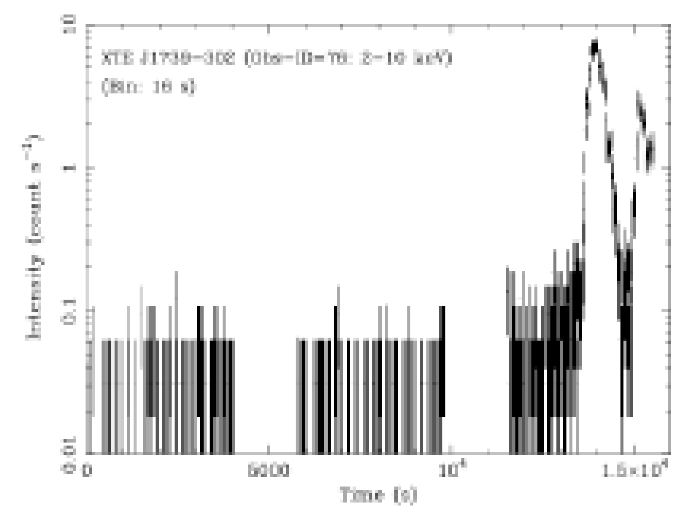




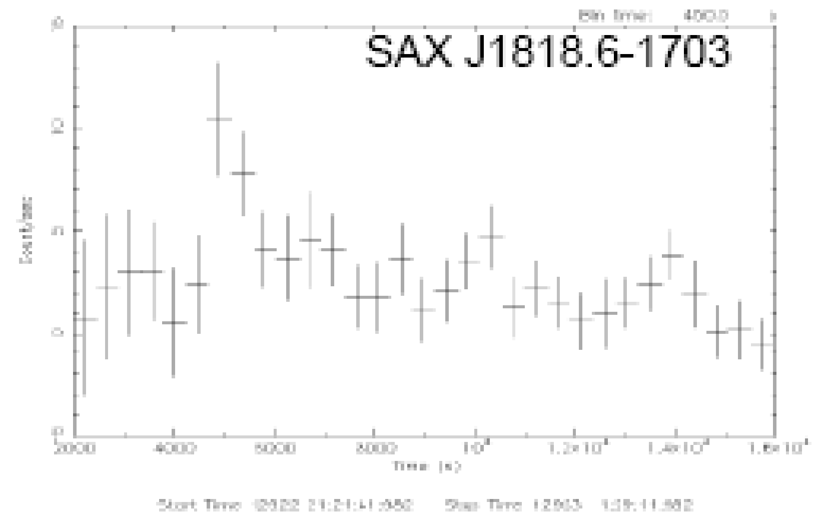
Limit cycle type behaviour !

A new class of HMXB: Supergiant Fast X-ray Transients

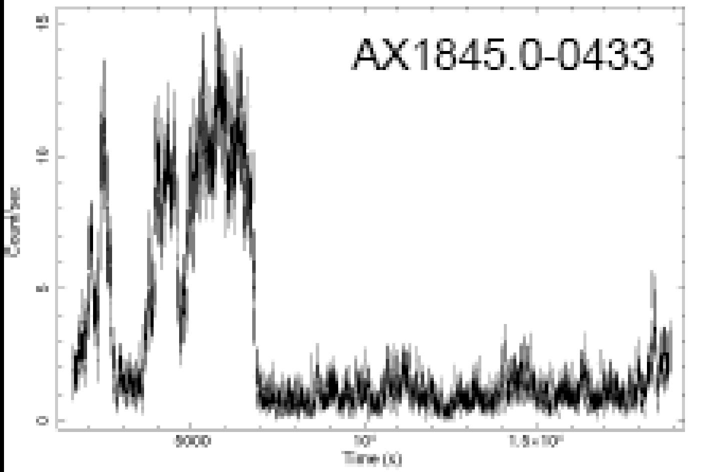




(Sakano et al. 2002)



(Sguera et al. 2005)

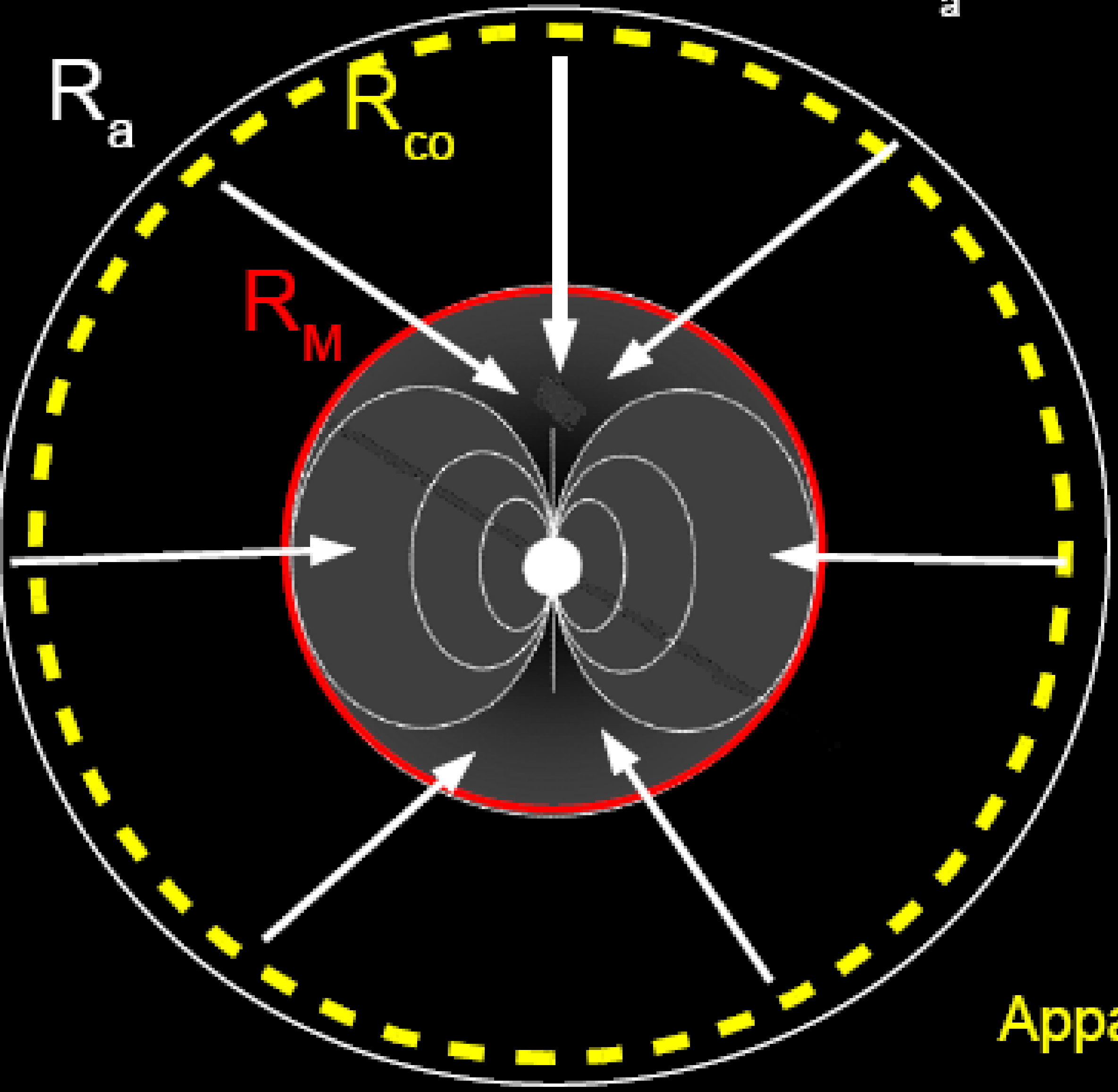


(Bozzo et al, in prep.)

DIRECT ACCRETION REGIME

$R_M \sim 3\times10^{9}\, B_{12}^{1/3}\, \dot{M}_{-6}^{-1/6}$ cm $<$ $R_{co} \sim 1.5\times10^{10}\, P_{spin1000}^{2/3}$ cm

$R_a \sim 4\times10^{10}\, v_8^{-2}$ cm



$$L_{acc} \sim \frac{G M_{NS} \dot{M}_{capt}}{R_{NS}}$$

$L_{acc} \sim 10^{36}$ erg s-1

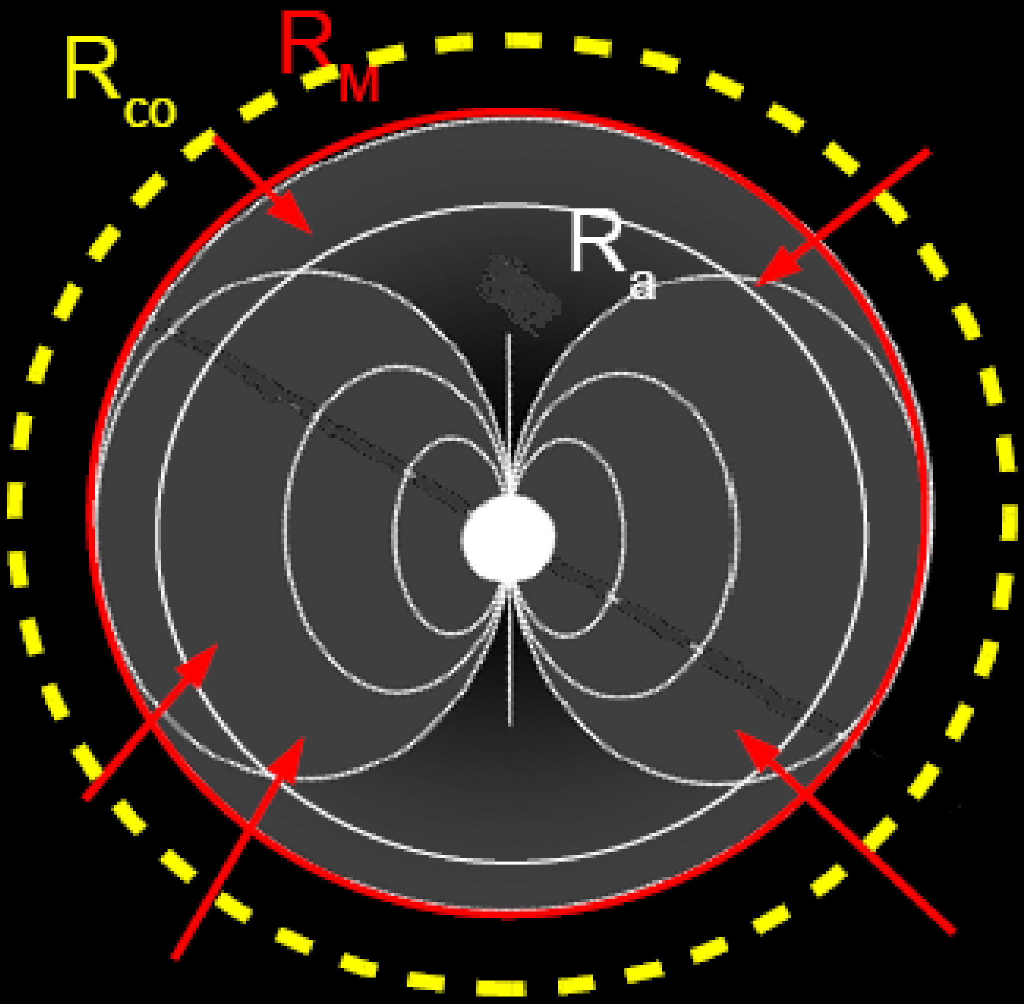
$\dot{M}_{capt} \sim 10^{16}$ g s^{-1}

$\dot{M}_w \sim 10^{-6}\, M_{sun}\, yr^{-1}$

Apparently it's working fine....

Magnetic Inhibition Regime

$$R_M \sim 4.5\times10^{10}\, B_{15}^{1/3}\, M_{-7}^{-1/6}\ \mathrm{cm} \quad \begin{array}{l} < R_{co} \sim 5\times10^{10}\, P_{spin6000}^{2/3}\ \mathrm{cm} \\ > R_a \sim 4\times10^{10}\, v_8^{-2}\ \mathrm{cm} \end{array}$$



Spin periods > 1000 s
Magnetar-like B-fields

(Bozzo et al 2008)

Conclusions

- Much progress in observations of nenutron star XRTs:
  transition to quiescence, quiescent multiwavelength spectra, etc
- Strong evidence for propeller regimes and centrifugal gap
- Evidence for radio pulsar shock emission regime in quiescent NS SXRTs
- Evidence for thermal emission from NS surface in SXRTs
- Present/future:
  - high S/N X-ray observations and spectroscopy (Chandra, XMM/Newton), timing, monitoring, searches for radio pulsed signal (Parkes, Arecibo)
  - Model development: disk-magnetsphere,propeller, jet launching, radio pulsar regime, spin up/down flips