INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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SCHOOL ON
NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

VARIABILITY (X-RAY BINARIER)

by

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3. Variability (x-ray binaries)

Acceleration mechanisms
(x-ray binaries, young SN)

In close binary with powerful, accretion-driven accelerator, ν-deposition expands star. Expansion $\Rightarrow$ increase in accretion rate. If $L_{CR} \propto \dot{M}$ then process runs away. ($T \sim 50$ yrs.)

Need feedback mechanism and variability.

R.J. Protheroe &
T. Stanev

CYGNUS X-3

BINARY SEPATATION = 1.80 SOLAR RADII
INCLINATION = 66 DEGREES
MAGNETIC MOMENT/RIGIDITY = 0.10 G.(CUBIC SOLAR RADII)/TV

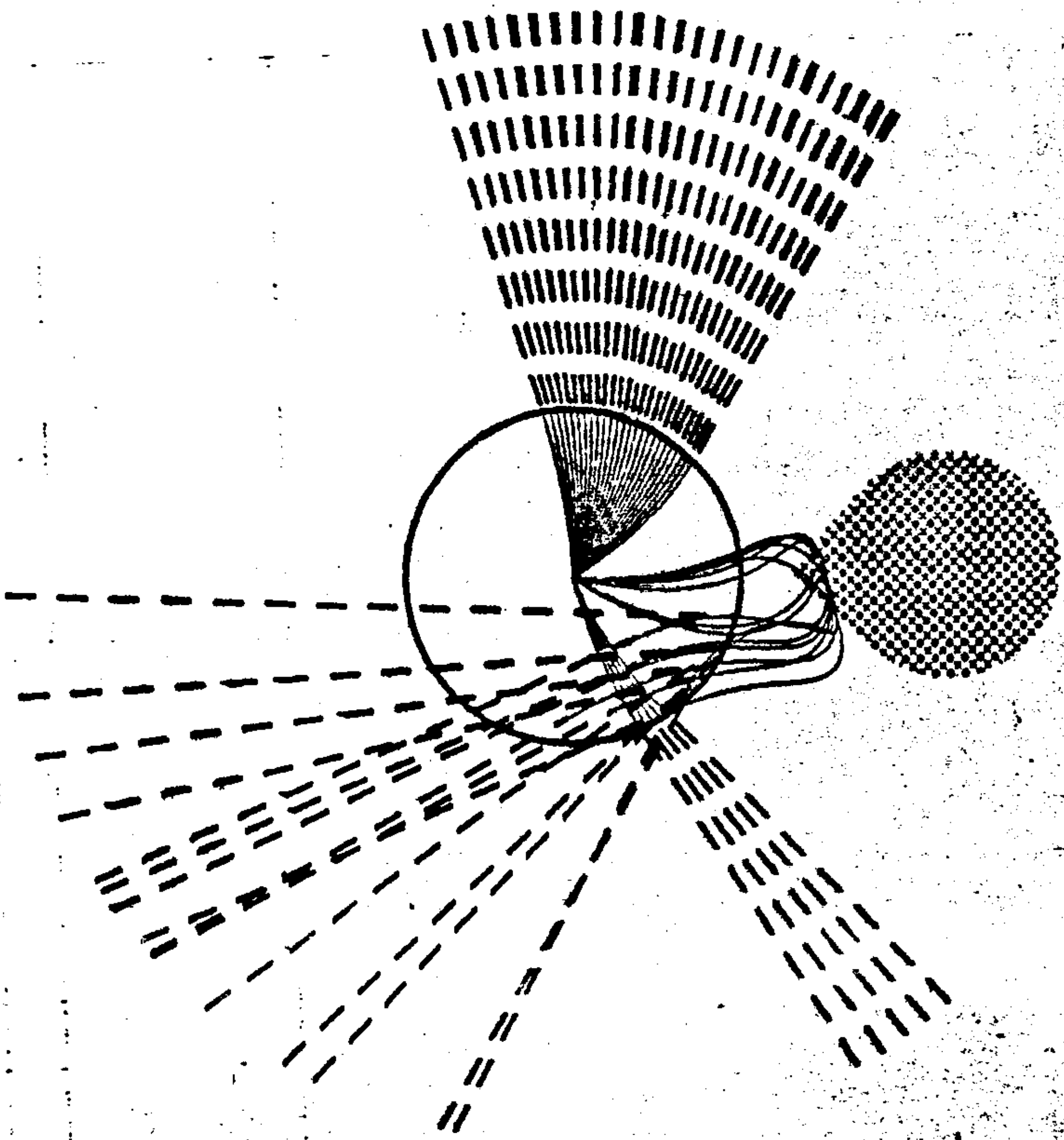
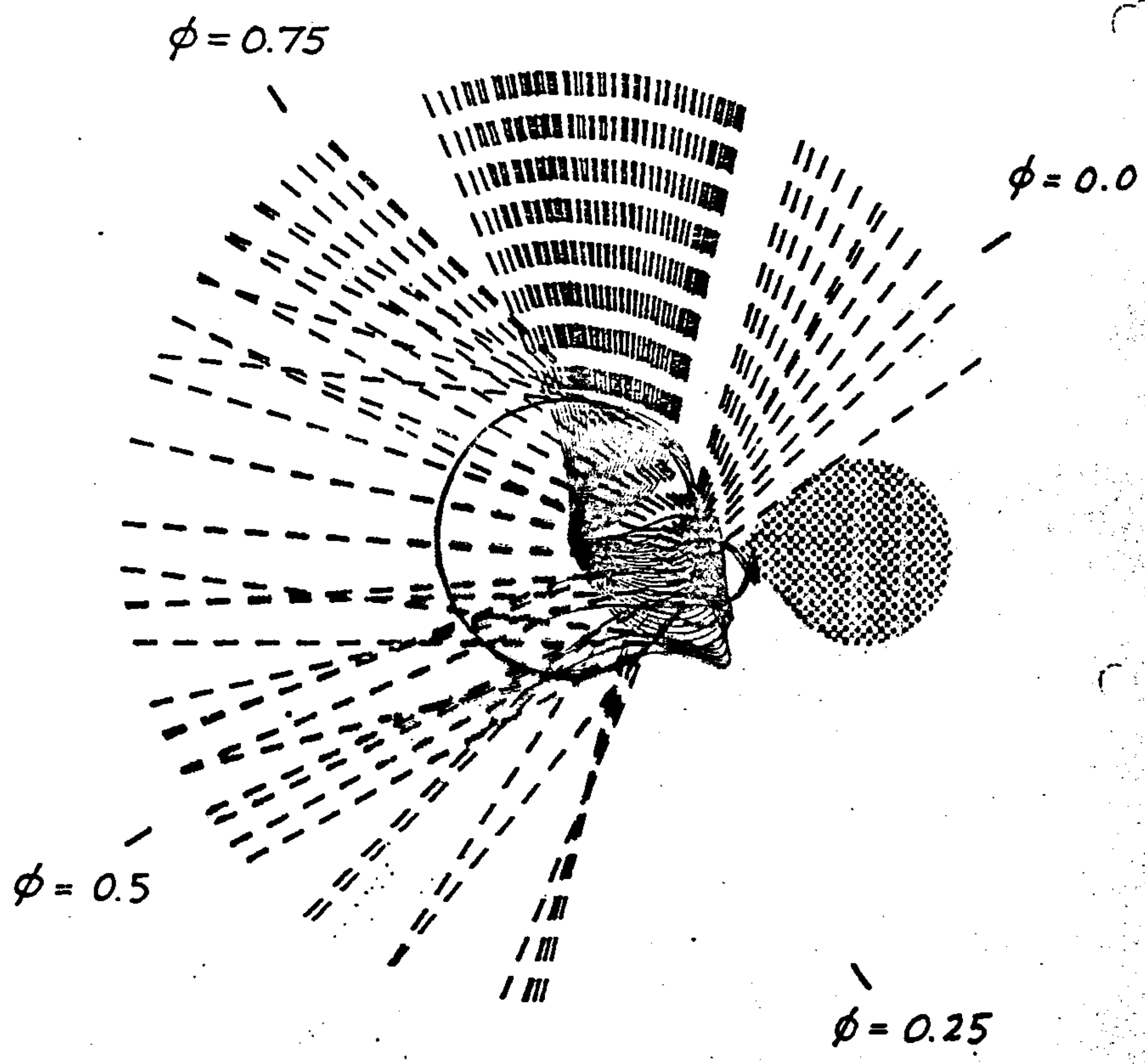
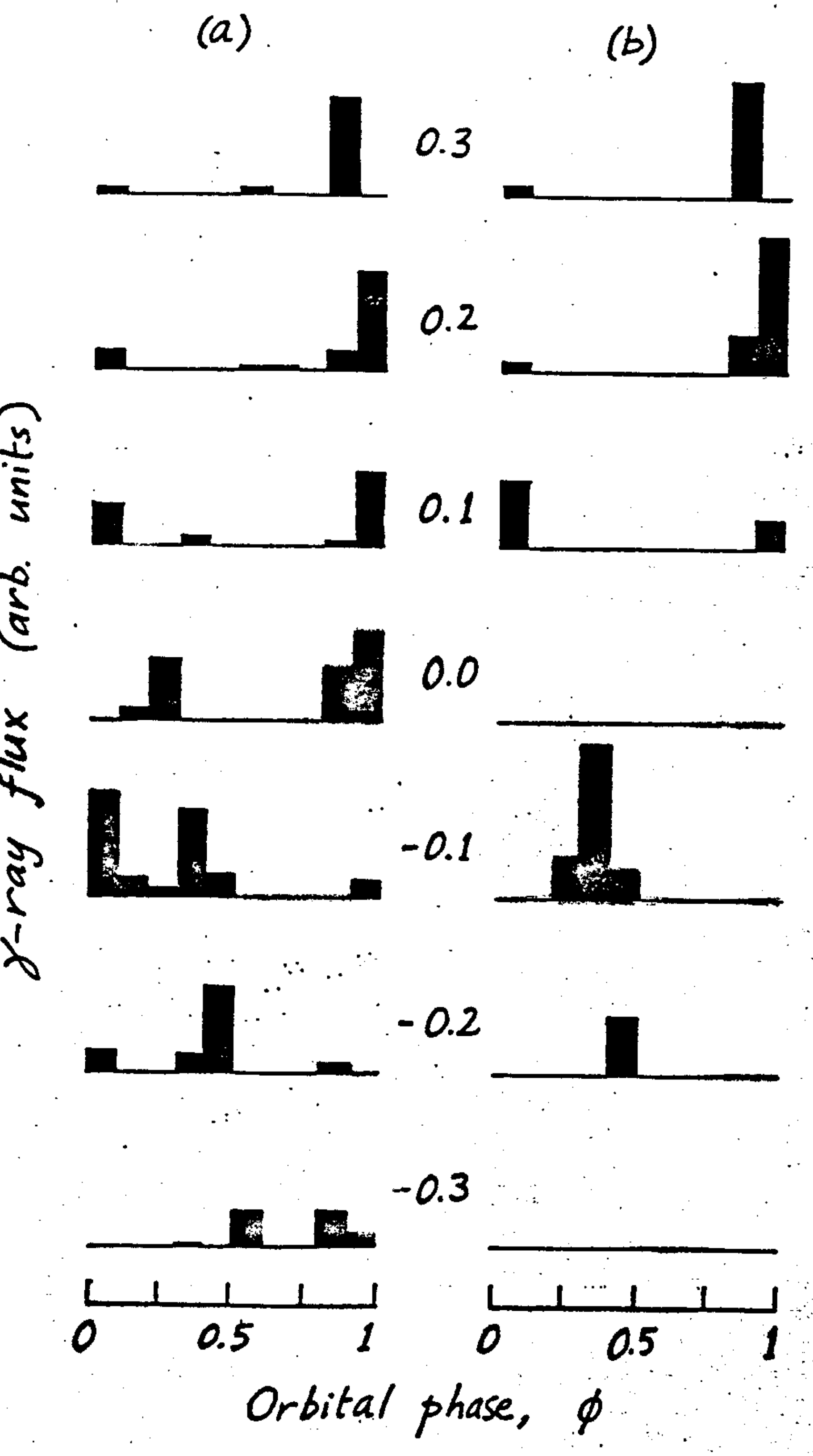


Fig. 1

Protheroe & Stanev Nature 328, p.136 (1987)



Protheroe & Stanev Nature 328 p. 136 (1987)



Properties of PeV emitting binaries

System	binary period (days)	Companion mass ($M_\odot$)	a / R_c *	distance (kpc)	L_{CR} ($\frac{erg}{sec}$)
Cyg X-3 =?	0.19	< 1 ?	1.6 - 2.0	$\gtrsim 10$	$\gtrsim 10^{39}$
* Vela X-1	8.965	23	12	1.4	$\sim 10^{37}$
LMC X-4	1.408	19	3.5	50	$\gtrsim 10^{41}$
Her X-1 $> 10^{12}$ G	1.7	2.4	6	4	$\sim 10^{38}$

* a from $P = 2\pi \sqrt{\dfrac{a^3}{G(M_{n.s.} + M_{companion})}}$

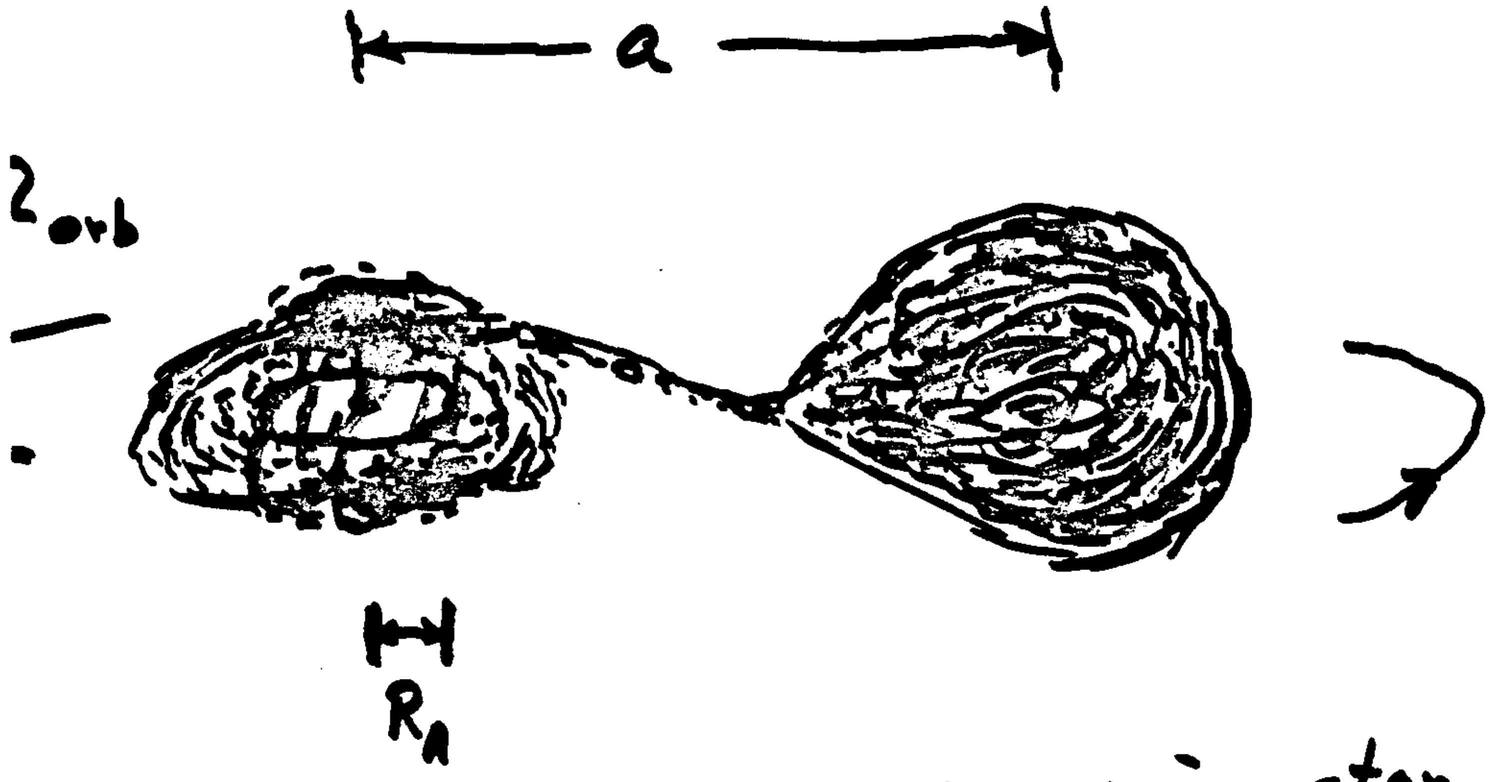
$M_{n.s.} \cong 1.4\, M_\odot$

R_c = radius of main sequence companion of mass M_c

(for ν-absorption, outer part of star is not important)

Alfven radius R_A:

characteristic radius at which <u>inward accretion flow</u> is balanced by <u>magnetic pressure</u> due to long-range (dipole component) field of neutron star.



neutron star "pulsar" has angular frequency Ω_p

companion star corotates with Ω_{orb}

R_A given by solution of

$$\frac{B^2}{8\pi} = \rho v^2$$

(1) $\dot{M} = \rho(r) 4\pi r^2 v$

(2) $v(r) \sim \sqrt{\frac{2GM_*}{r}}$

(3) $B(r) = \frac{\mu_*}{r^3}$

in near zone only, i.e. $r < R_L$

(4) $R_L = c/\Omega_p$

-4) in ↑ give

$$\boxed{= \mu^{4/7} (2\dot{M})^{-2/7} (2GM)^{-1/7}}$$

$\mu^* = B_* R_*^3)$

f $R_A \ll R_L$ then "light cylinder radius"

ccretion disk penetrates

nagnetosphere" and accretion onto n.s.

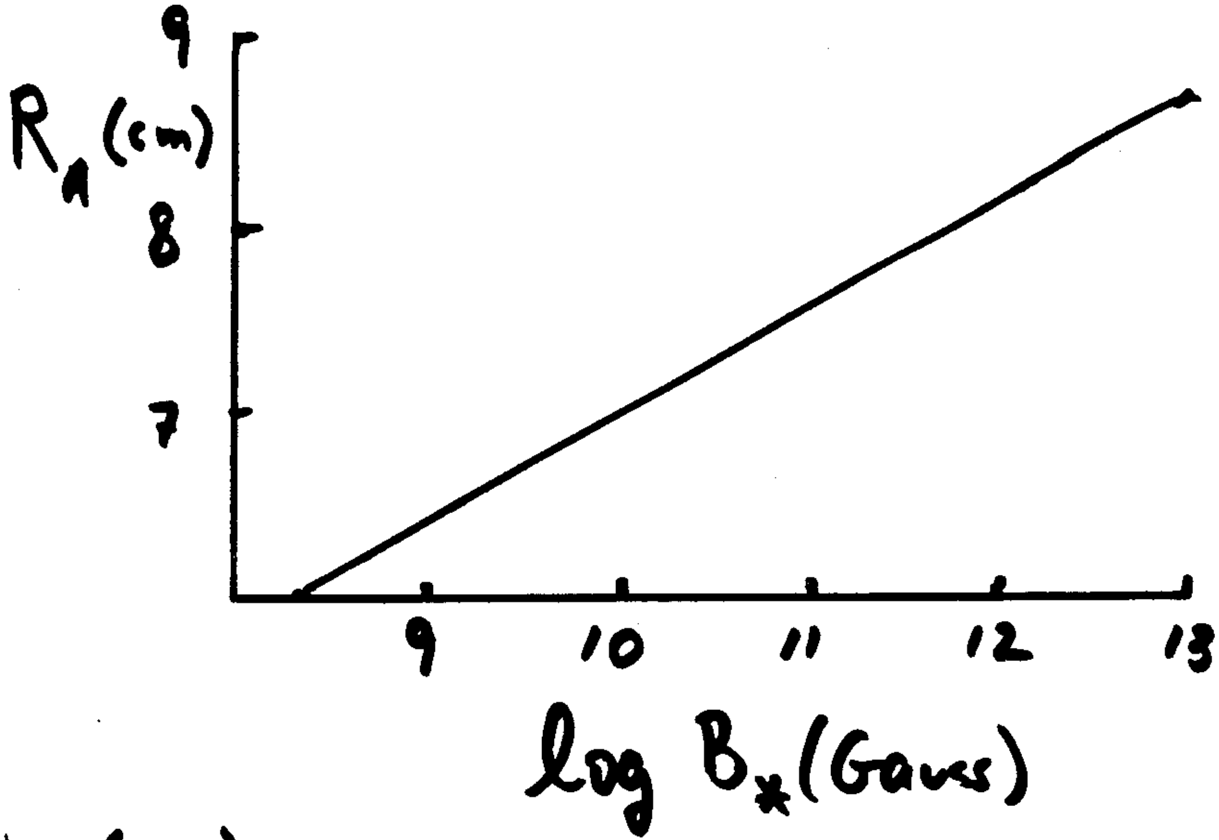
ccurs along field lines onto polar regions

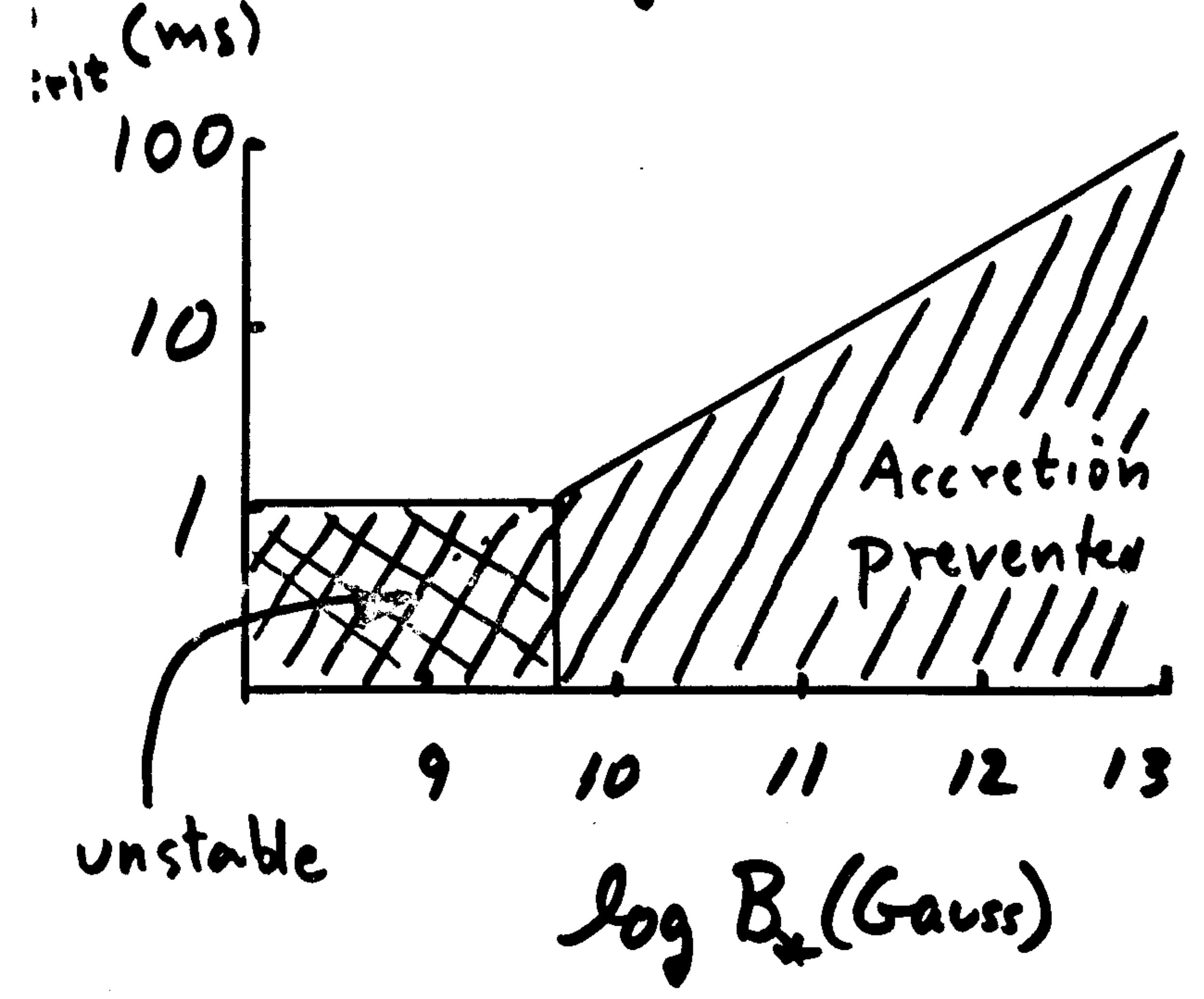
References: • Katz, High Energy Astrophysics

Frank, King & Raine, Accretion Power in Astrophysics

Pringle & Wade, X-ray Binaries

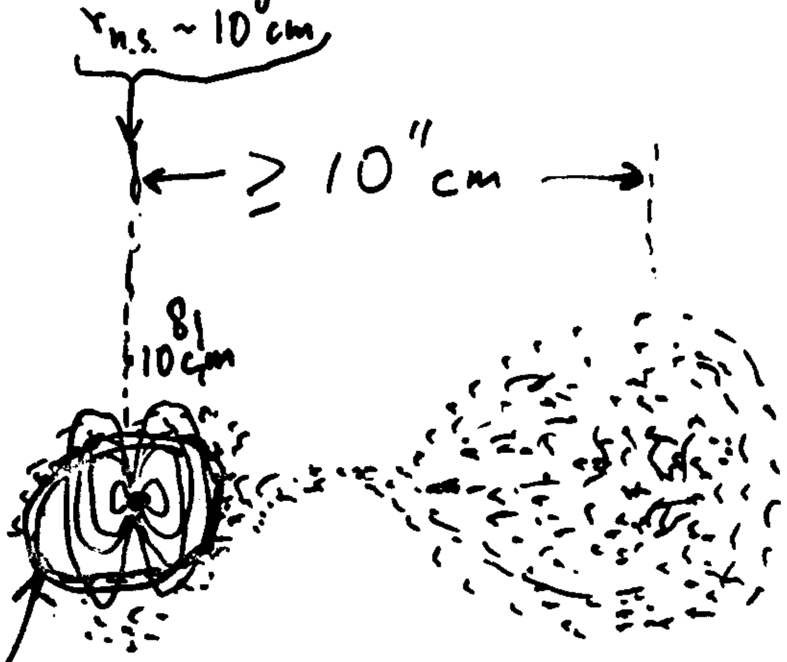
For $\dot{M} = 10^{18}$ g/s (~ Eddington limit)





Example of an accretion-driven mechanism

Shock Acceleration : Kazanas & Ellison
(Nature 319 30 Jan 86)



shock when $\rho v^2 \sim \frac{B^2}{8\pi} \Rightarrow r \lesssim 10^8$ cm

Strong B field: $B \sim \frac{10^{30}\text{ Gauss cm}^3}{r^3}$

E_{max} for $T_{accel.} \sim T_{synchrotron}$

$E_{max} \sim 10^5 - 10^8$ GeV

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hanging accretion rate ($\Delta\rho$)

$\Rightarrow$ change Alfven radius

$\Rightarrow$ change E_{max} ($+\Delta\rho \Rightarrow -\Delta E_{max}$)

- Shock may occur in accretion flow at Alfven radius but full accretion energy is not released unless $B_* \gtrsim 10^8$ Gauss so $R_A \sim R_*$.

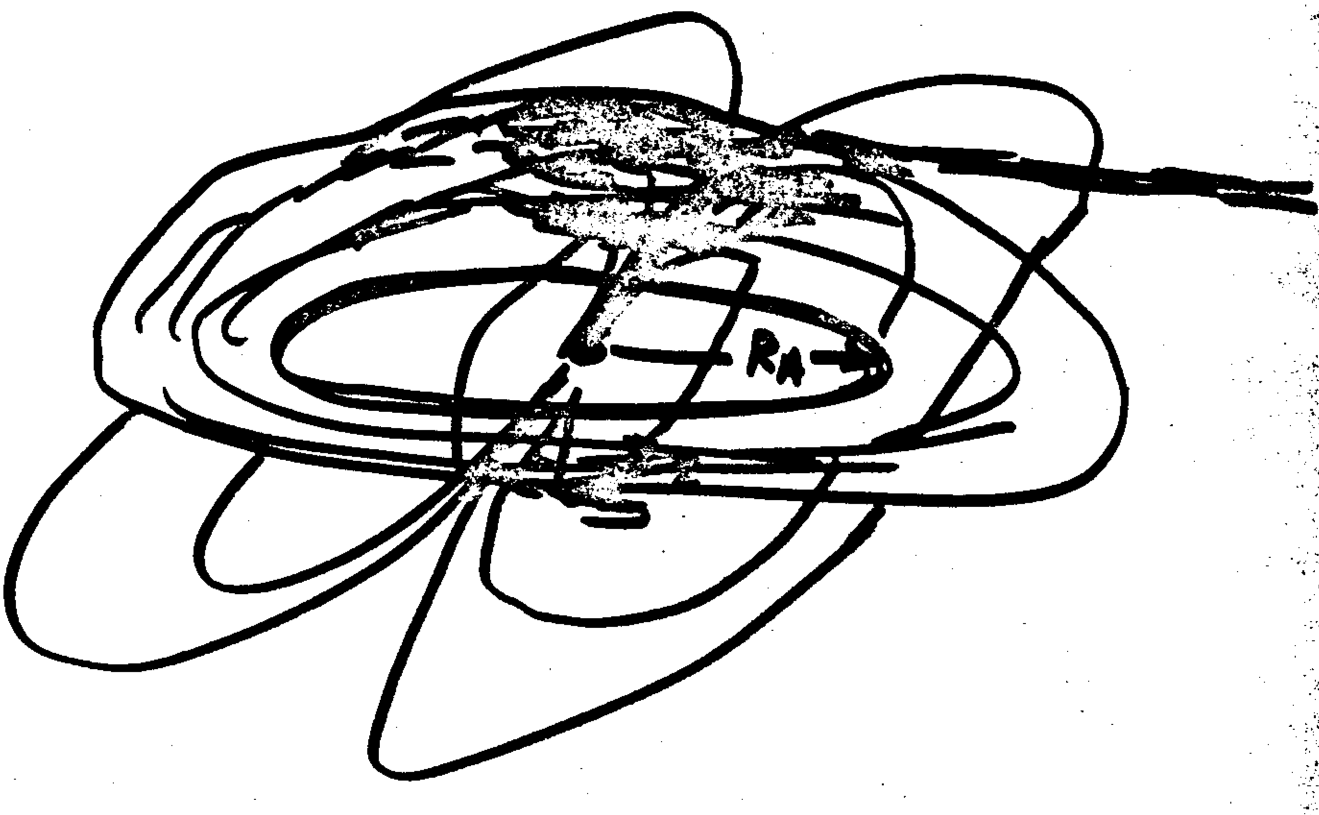
- Shock may occur near polar cap for $B_* \gg 10^8$ Gauss but then $\frac{B^2/8\pi}{\rho v^2} > 1$ in acceleration region and shock acceleration fails (because B field dominates plasma flow rather than vice versa

Conclusion: shock acceleration works only for accretion onto n.s. with low B
[Kazanas & Ellison Nature 319 380 (1986)]

Differential rotation of pulsar and disk (homopolar generator)

Chanmugam + Brecher, Nature 313, 767 (1985)

Cheng & Ruderman



$$E = \frac{e}{c} v B \Delta r \Big|_{R \sim \Delta r \sim R_A}$$

$$v_{\text{kepler}}(R_A) = \sqrt{\frac{GM_*}{R_A}}$$

Problem: show

$$E_{max} \sim 2 \times 10^4 \text{ TeV } B_8^{-3/7} L_{38}^{5/7}$$

Both shock acceleration &

homopolar generator require

$B_* \gtrsim 10^8$ G to work

$\therefore$ fail for Her X-1, $B_* > 10^{12}$ G

B_* (Cyg X-3) not known

Another possibility: accretion

generated turbulence in

MHD accretion flow

(more energetic analog of

acceleration of 1-10 GeV

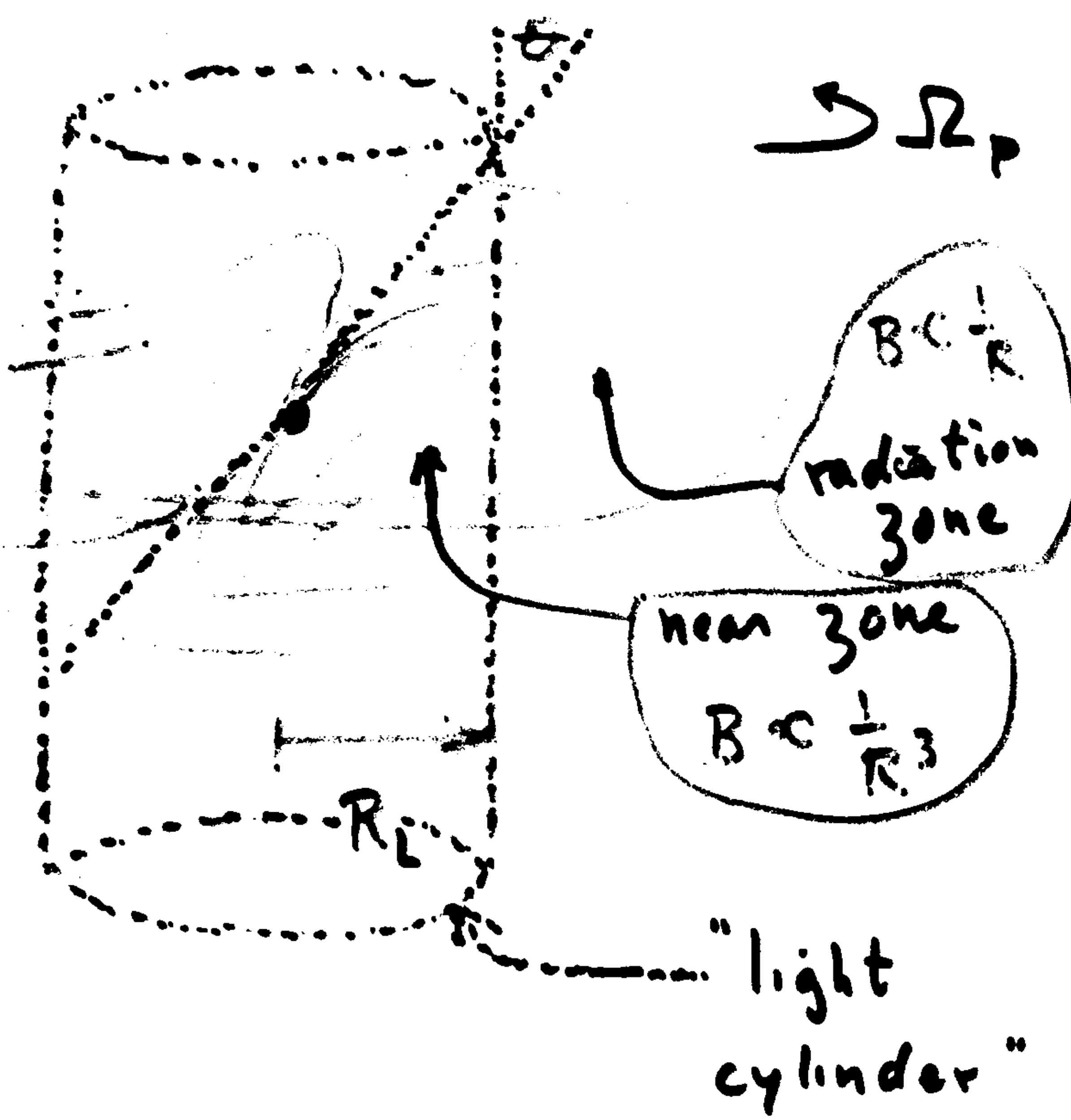
particles by turbulence on

the Sun)

Wang, Astron. & Space Sci

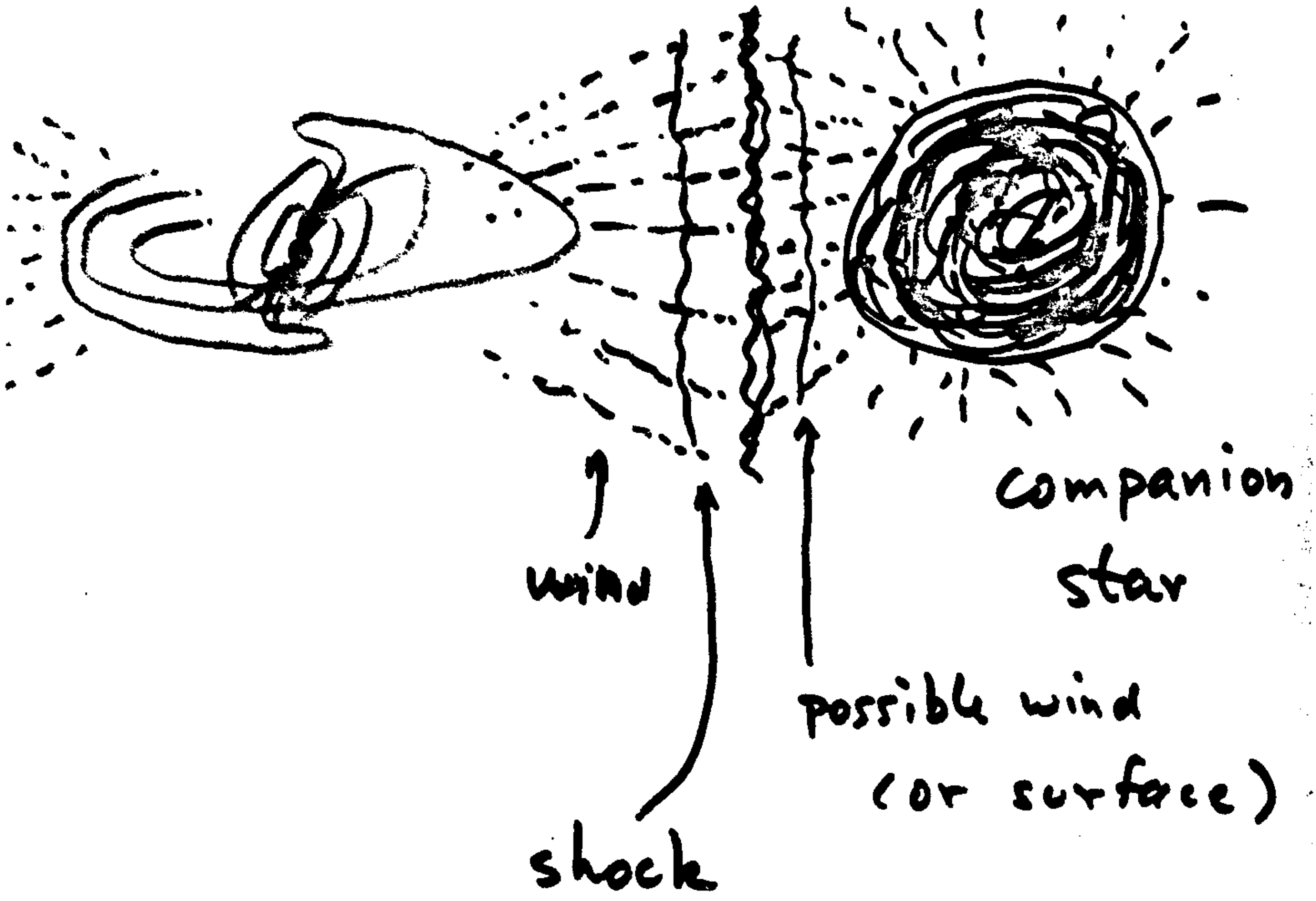
<u>121</u>, 193 (1986).

what happens if T[illegible] ≠ T[illegible] ?



$$L_D = \frac{2}{3}\frac{\mu^2 \Omega_p^4}{c^3}\sin^2\theta$$

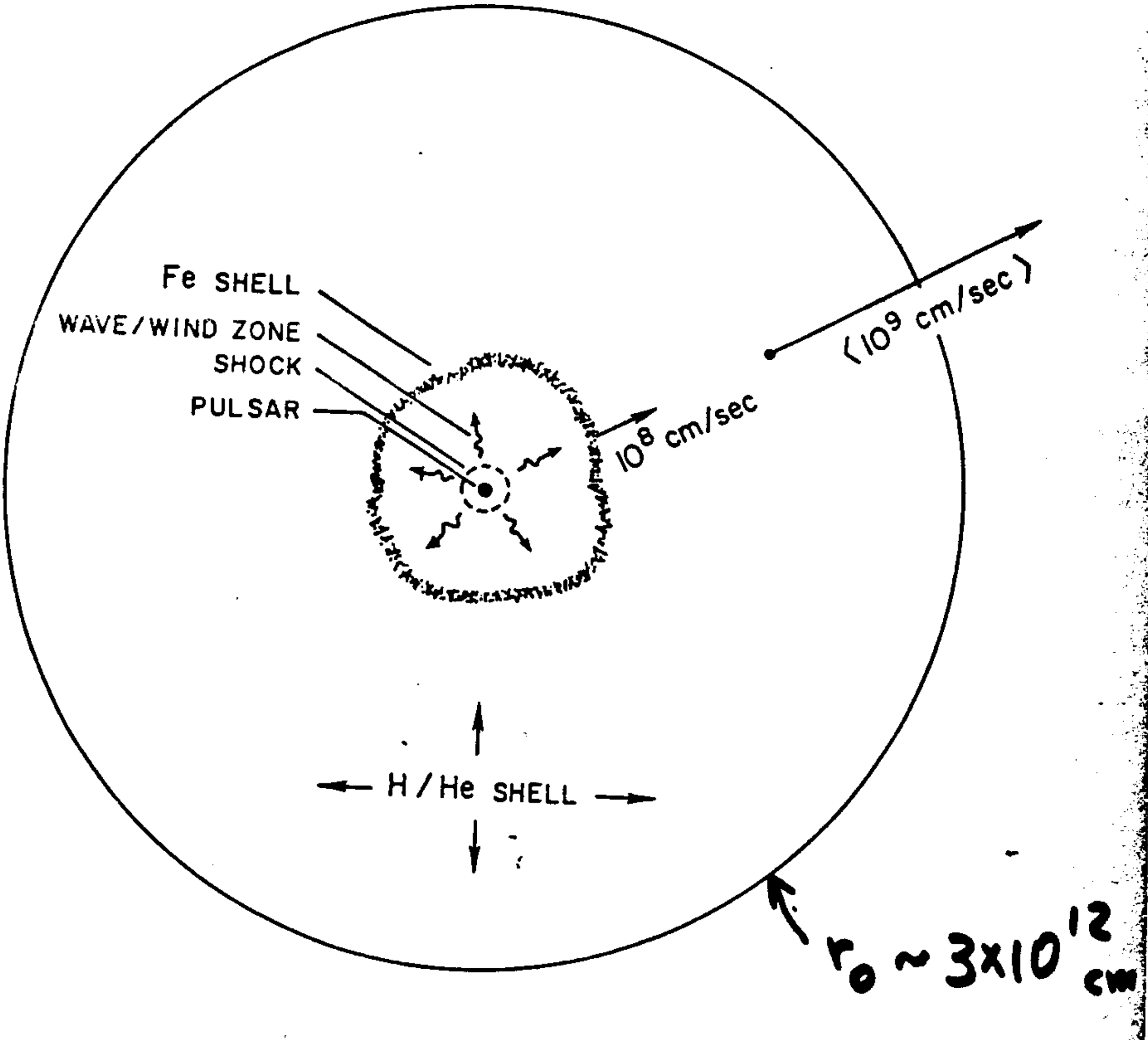
This [illegible] goes into relativistic, positronic wind of $e^\pm$ plasma created by electrons pulled off n.s. surface by strong $v \times B$ force, which then cascade.



Bignami, Maraschi & Treves
Astron. Astrophys. 55, 155 (1977)
proposed this as site of X-rays
in Cyg X-3.

The associated shock could also serve
as a site for acceleration
(TKG & A. Harding)

Michel, Kennel & Fowler, Science



Acceleration of particles:

a) How much power?

b) Character of beam —
Energy spectrum, E_{max}?

a) Pulsar power

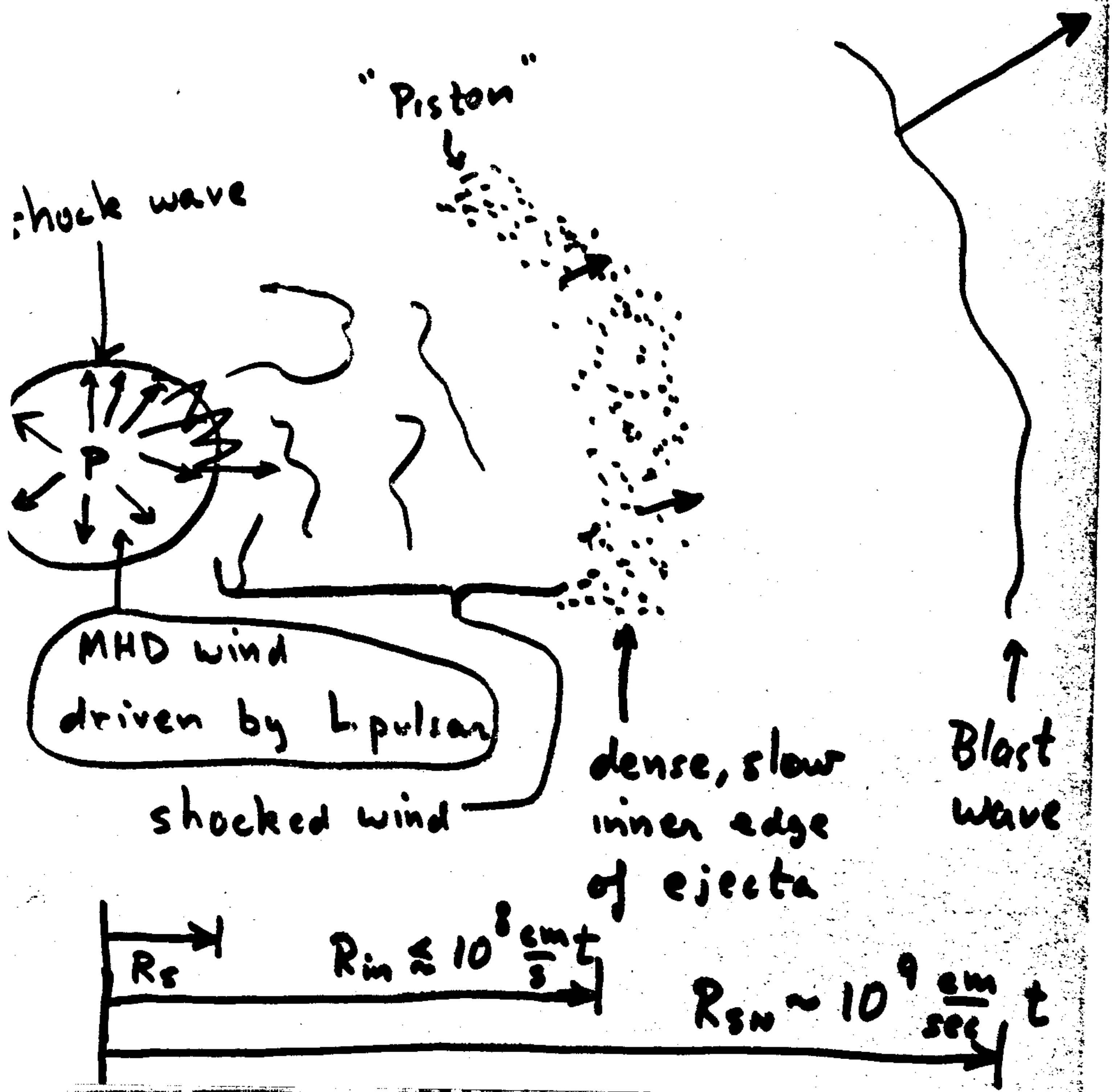
$$L = \frac{2}{3}\frac{\mu^2 \Omega^4}{c^3}\sin^2\theta \sim 2\times 10^{39}\,\frac{\text{erg}}{\text{s}} \times \left(B_{12}^2\, P_{10}^{-4}\right)$$

$\mu = B_* R^3$, $\Omega = \frac{2\pi}{P}$. as example
scale to $B = 10^{12}$ Gauss, $P = 10$ ms.
[Stability requires $P \gtrsim 1$ ms]

$$\tau_{acc} \sim \frac{\frac{1}{2} I \Omega^2}{L} \sim 3000\,\text{yrs}\left(\frac{P_{10}}{B_{12}}\right)^2$$

b) Spectrum of beam – depends on acceleration mechanism. One possibility:

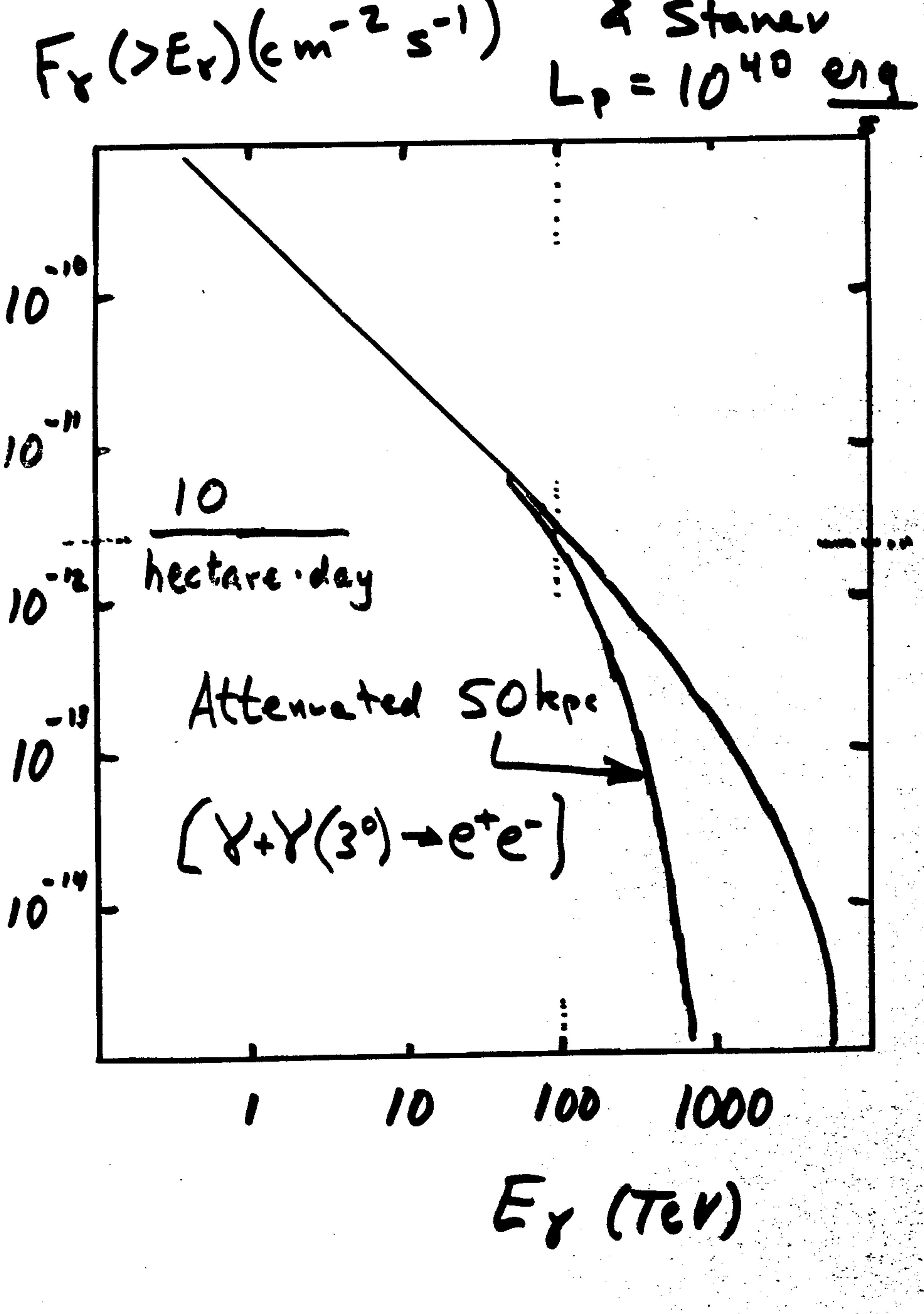
TKG, Harding & Stanev
NATURE 329, 314 (1987)



Apr 12

TKG, Harding & Stanev

$L_p = 10^{40}$ erg/s



$$\frac{L}{4\pi R_s^2 c} = \frac{\int L\,dt}{\frac{4}{3}\pi R_{in}^3} \quad \left\{ \begin{array}{l} \text{Pacini \& Salvati} \\ \text{Rees \& Gunn} \end{array} \right.$$

$$\Rightarrow \frac{R_s}{R_{in}} \sim \sqrt{\frac{\beta_{in}}{3}} \lesssim 0.1$$

Given $R_{in} = u_{in} t$ calculate

$$B_s \sim 3 \text{ Gauss } B_{12} P_{10}^{-2} t_{yr}^{-1} u_8^{-3/2}$$

$B(r) = B_* / r^3 \quad r \leq$ light cylinder

$B(r) = \frac{B_*}{(r_{L.C.})^3} \frac{r_{L.C.}}{r} \quad r$ in radiation zone

E_{max} from $R_{Larmor} < R_s$

$$R_s \sim 10^{14} \text{cm } t_{yr} u_8^{3/2}$$

$$\boxed{E_{max} < e B_s R_s \sim 8 \times 10^4 \text{ TeV} (B_{12} P_{10}^{-2})}$$

note cancellation of t + u_{in} !