Radio PSR 50years

2023年12月16日 星期六 下午8:42

V.S. Beskin Physics-Uspekhi 2018

1. PSR chronicles:

🟩 是我自己加的

(1.1) Prehistoric (< 1967)

Neutron stars 1930s
- Landau 1932
- Baade & Zwicky 1934
- TOV 1939
- ......

"Cosmic Rays from SNe"

> In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place, where also will be mentioned some observations that tend to support the idea of stellar bodies made up mainly of neutrons.

Pacini 1967 "Energy Emission from a NS"

NS → Crab Nebula
(not obs) (observed)

$R_{NS} \sim 10^6$ cm $\Rightarrow B \sim 10^{10} \sim 10^{14}$ G

$\Downarrow$

MHD waves ......
Relativistic particles ......

$B_\odot \sim 1 \sim 10$ G (surface)
$R_\odot \sim 10^{11}$ cm

[没说射电强...]

No dedicated searches on radio active NS ......

Until Bell & Hewish (Hewish et al. 1968) 1967.7

(Pulsar = Pulse + Quasar)

Fishman et al. 1969: Obs of pulsed hard X-ray from NP 0532 1967.6 气球

[Charles Schisler, 美国空军雷达员 1967 → Crab pulsar]

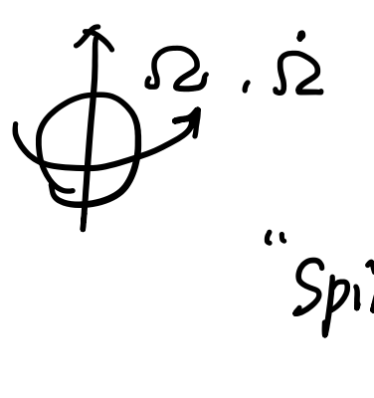
(1.2) Hellas (1968-1973)

- Simple & Visual ideas.

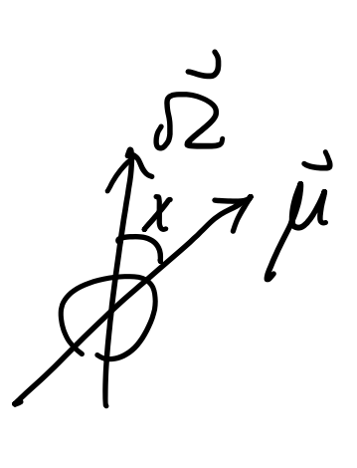
最初 & 最简单: a magnetized ball rotating in a vacuum.
↳ main properties (v)

超准 TOA → rotating NS
Radio 供能 ↗
(Gunn & Ostriker 1969, 1970)

Estimation of B:



$\dot\Omega < 0$ (for most PSR)
"Spin down"



$$-I\Omega\cdot\dot\Omega = \frac{1}{6}\frac{B_0^2\Omega^4R^6}{c^3}\sin^2\chi$$

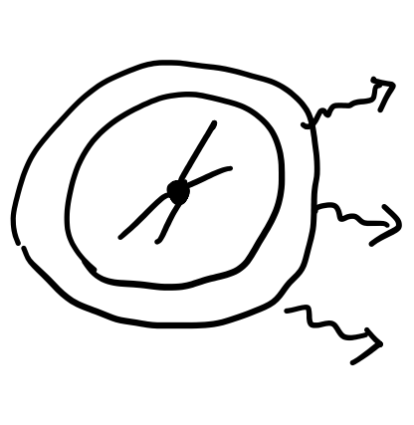
自转能损 偶极辐射

$\Rightarrow B_{12} \simeq (P\cdot\dot P_{15})^{1/2}$

[Validity: Crab PSR: $P \simeq 33$ ms, $\dot P_{-15} = 420$

$$I\Omega\cdot\dot\Omega \simeq (2\times10^{33}\,g)\cdot(10^6\,cm)^2\cdot(33\,s^{-1})\cdot\left(\frac{420\times10^{-15}}{(33\times10^{-3})^2}\right) \sim 10^{38}\,erg\cdot s^{-1}$$

与 Crab Nebula 光学观测 ✓



$\tau_D \simeq P/2\dot P \simeq 10^3$ yr. (1968-1054)]

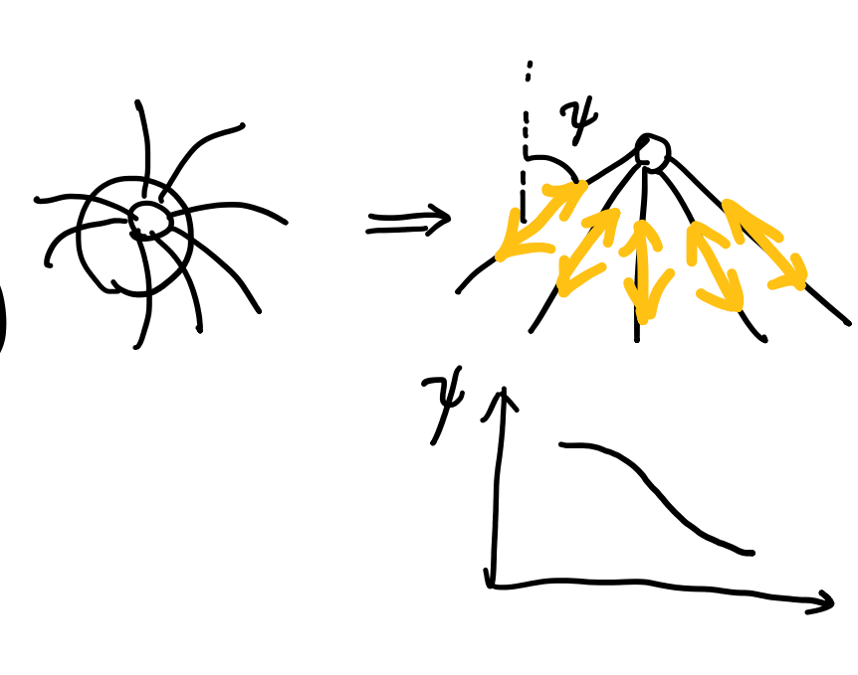
Rotating Magnetic field ⇒ Electric Field

$$E \sim (v/c)\cdot B,\quad \Delta V_{max} \simeq \left[\left(\frac{\Omega R_{NS}}{c}\right)\cdot B_0\cdot R_{NS}\right]_{max} \quad \nearrow \text{SI}\to\text{Gauss}$$

$$\simeq \frac{(10^2)\cdot10^6}{10^{10}}\cdot10^{4}\cdot10^6\,(10^2) \sim 10^{20}\,V$$

⇐ Cosmic Rays

RVM model 1969 (Radhakrishnan & Cooke)



However, PSR couldn't surrounded with vacuum...

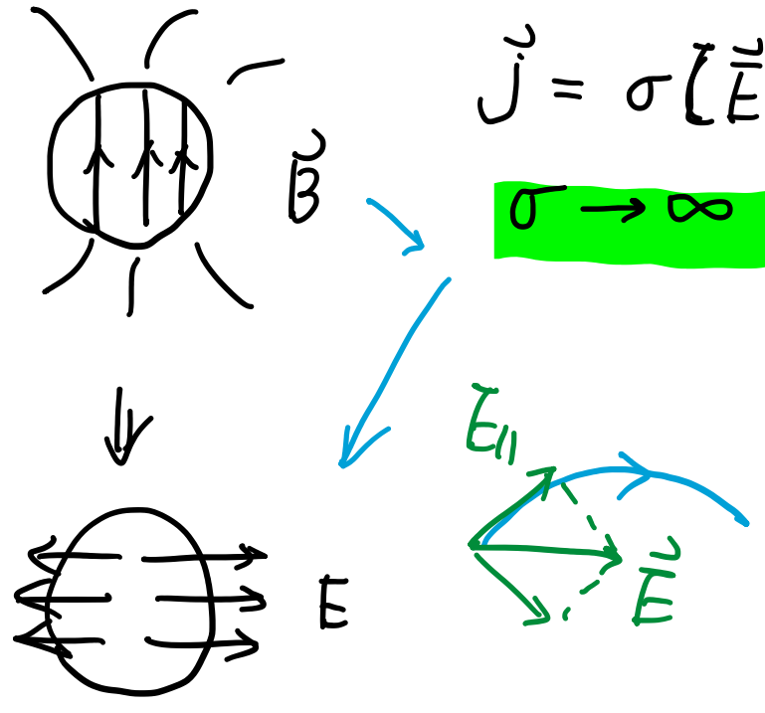
Sturrock 1971: $\gamma + (B) \to e^\pm + (B)$
↓
magnetosphere ......

how this process actually happens?

[$-I\Omega\dot\Omega = E_{dipole}$ is invalid actually...]

First, in vacuum rotating NS:

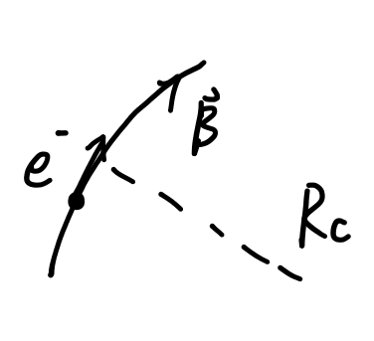
internal: Based on B, G, I 1983 PSR MAGNETO
(其实不一定这样磁化)
我暂且这么想
(所以跟 magnetization 有关?)



$$\vec j = \sigma\left[\vec E + \frac{(\vec\Omega\times\vec r)}{c}\times\vec B\right]$$

$$\sigma\to\infty \Rightarrow \vec E + \frac{(\vec\Omega\times\vec r)\times\vec B}{c} = 0$$

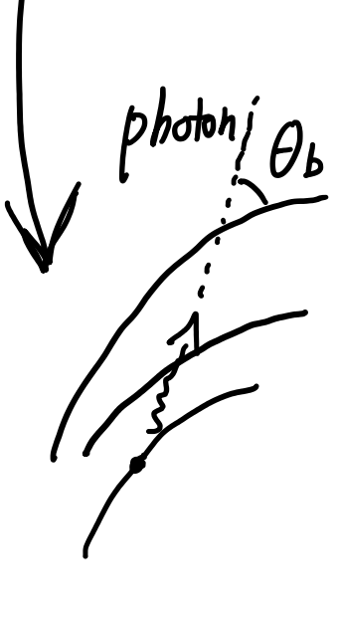
$E_\parallel \sim \frac{\Omega R}{c}B$
↓
加速 e^- ⇒ $\mathcal{E}_e \gg m_ec^2$



Curvature Radiation: $\omega_{cur} \sim \frac{c}{R_c}\left(\frac{\mathcal{E}_e}{m_ec^2}\right)^3$

对于电子: $$\frac{d\mathcal{E}_e}{dl} = eE_\parallel - \frac{2}{3}\frac{e^2}{R_c^2}\left(\frac{\mathcal{E}_e}{m_ec^2}\right)^4$$

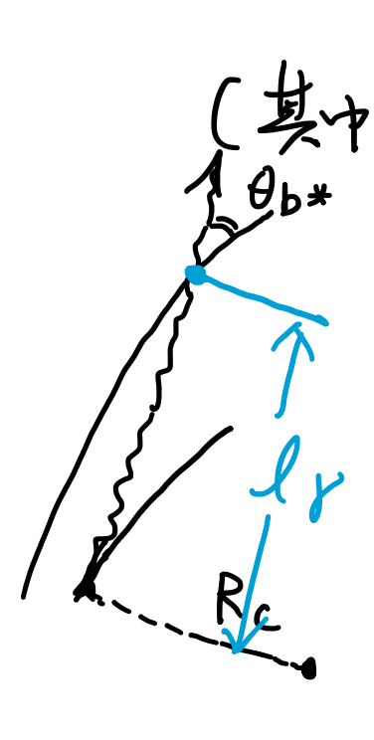
$$\Rightarrow \mathcal{E}_{max} \sim \left(\frac{R_c^2E_\parallel}{e}\right)^{1/4}\cdot m_ec^2 \sim (10^7 - 10^8)\,MeV$$



$$w = \frac{3\sqrt{3}}{16\sqrt{2}}\frac{e^3B\sin\theta_b}{\hbar m_ec^3}\exp\left(-\frac{8}{3}\frac{B_{cr}}{B\sin\theta_b}\frac{m_ec^2}{\mathcal{E}_{ph}}\right)$$

(γ-B 反应发生概率) $\theta_b\uparrow$, $w\uparrow$

(其中 $B_{cr} = \frac{m_e^2c^3}{e\hbar} \simeq 4.4\times10^{13}$ G, $\hbar\omega_{B_{cr}} = m_ec^2$)



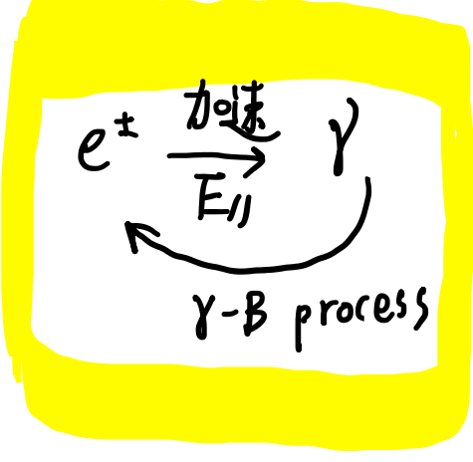
mean free path estimation:

$$\sin\theta_{b*} \simeq \frac{8}{3}\cdot\frac{B_{cr}}{B}\cdot\frac{m_ec^2}{\mathcal{E}_{ph}}$$

$l_\gamma \simeq \left(\frac{R_c}{\Lambda}\right)\cdot\sin\theta_{b*}$ (根据 field line 和 NS 位形)

$\Lambda \sim 20$, $l_\gamma \ll R_c$

※ γ-B 过程 prohibited for γ // B ($\theta = 0$)



→ stops when $E_\parallel$ screened by + + + + ↓↓↓↓ - - - -

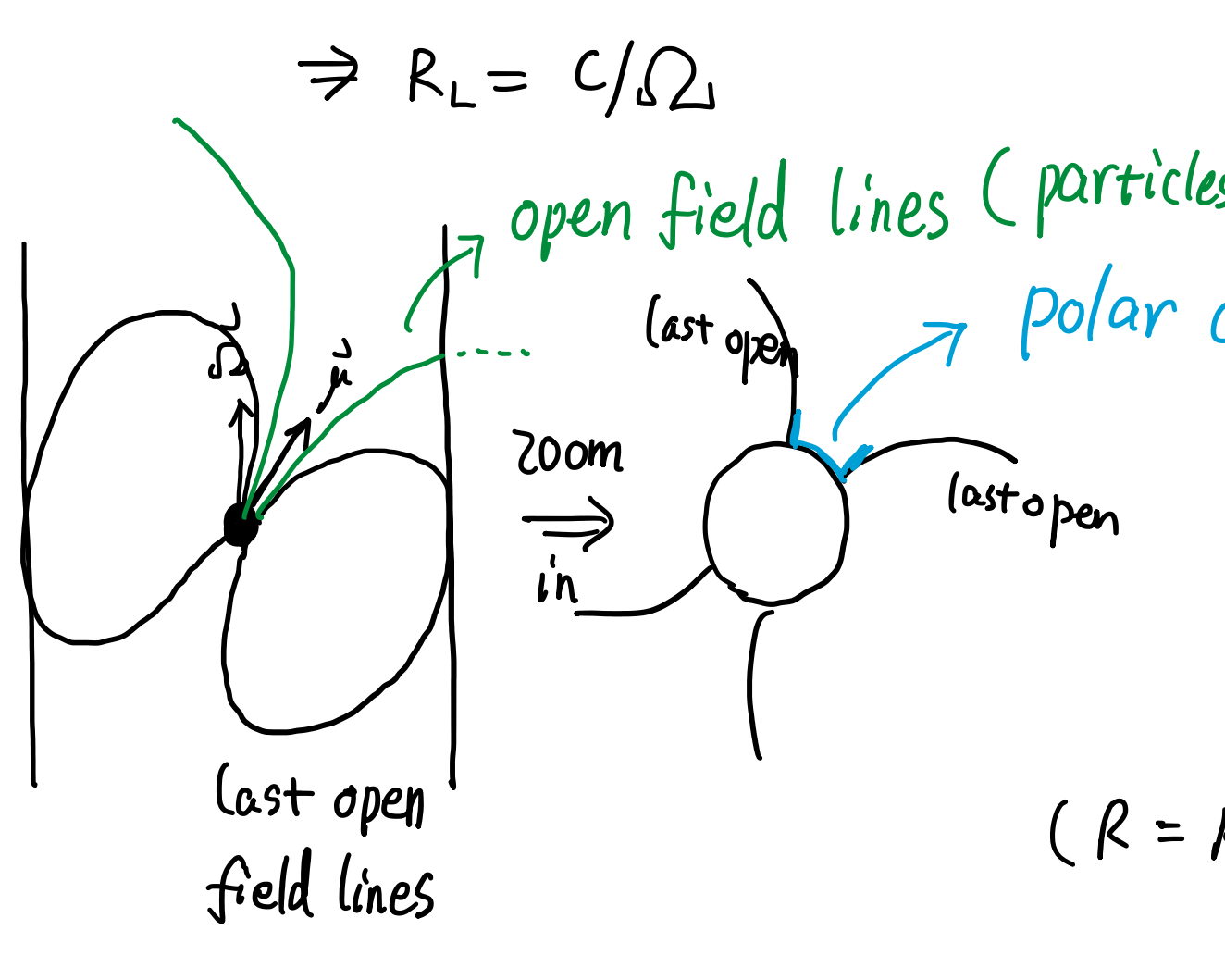
(※ PSRs should be positron sources)

$e^\pm$ plasma rigidly rotates with PSR (like Earth & Jupiter's magnetospheres)

but ...... of course fails in large distances......

- when co-rotating velocity = c, $\Omega\cdot R_L = c$

$\Rightarrow R_L = c/\Omega$



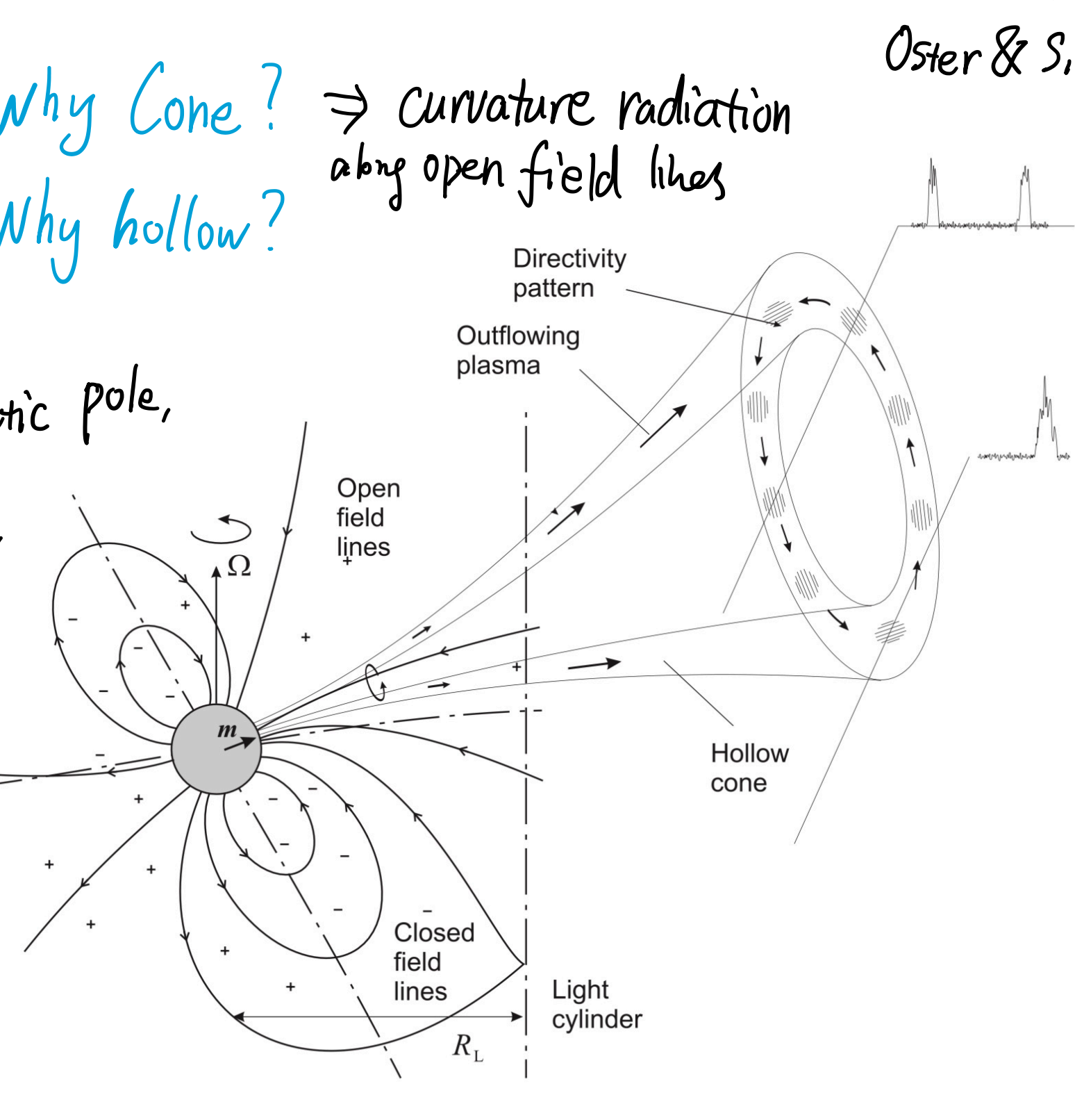
$R_{cap} \simeq R_0$ (aligned)
$= \left(\frac{\Omega R}{c}\right)^{1/2}R$
($R = R_{NS}$)

To explain observation: kinds of radiation cone models...

A classical one: "Hollow cone Model" (RVM 1969, Oster & Sieber 1976)

Why Cone? ⇒ curvature radiation along open field lines

Why hollow?
↙
near magnetic pole,
磁力线直,
$\theta_b \simeq 0$,
γ-B 不显著,
且曲率辐射弱......



Measure/Define Magnetosphere parameters:

3 most important
- electric charge density ρ_{GJ}
- multiplication factor λ
- magnetization para. σ_M

(1) ρ_{GJ}: Goldreich & Julian 1969

$\vec E + \vec\beta\times\vec B = 0$
$\vec\beta = k\vec B + (\Omega r/c)\sin\theta\cdot\hat\phi$

$$\hookrightarrow \rho_{GJ} = \frac{\nabla\cdot\vec E}{4\pi} = -\frac{\vec\Omega\cdot\vec B}{2\pi c}\left[1-\left(\frac{\vec\Omega\times\vec r}{c}\right)^2\right]^{-1}$$

$$\simeq -\frac{\vec\Omega\cdot\vec B}{2\pi c} \quad \text{(inner magnetosphere)}$$

if current exist

A balanced magnetosphere. $n_{GJ} = \frac{|\rho_{GJ}|}{e} \sim 10^{12}\,cm^{-3}$ (表面附近)

typical current density: $j_{GJ} = \rho_{GJ}\cdot c$

(2) $\lambda = \frac{n_e}{n_{GJ}}$

(secondary particle exceeds ρ_{GJ})

(3) $\sigma_M = \frac{1}{4\lambda}\frac{eB_0\Omega^2R^3}{m_ec^4}$ (Michel 1969)

recall $W_{tot} = -I_r\Omega\dot\Omega = \frac{1}{6}\frac{B_0^2\Omega^4R^6}{c^3}\sin^2\chi$

when W_{tot} totally turn into particles' out flowing energy.

$W_{tot} = \dot N\cdot(\Gamma m_ec^2)$
$= (\lambda n_{GJ}\cdot\pi R_0^2\cdot c)\cdot(\Gamma m_ec^2)$

$$\Leftrightarrow \frac{1}{6}\frac{B_0^2\Omega^4R^6}{c^3}(\sin 60)^2 = \lambda\cdot\frac{\Omega B_0}{2\pi ce}\cdot\pi\frac{\Omega R}{c}\cdot R^2\cdot c\cdot\Gamma m_ec^2$$

$$\Rightarrow \Gamma = \frac{1}{4\lambda}\cdot\frac{eB_0\Omega^2R^3}{m_ec^4} \equiv \sigma_M$$

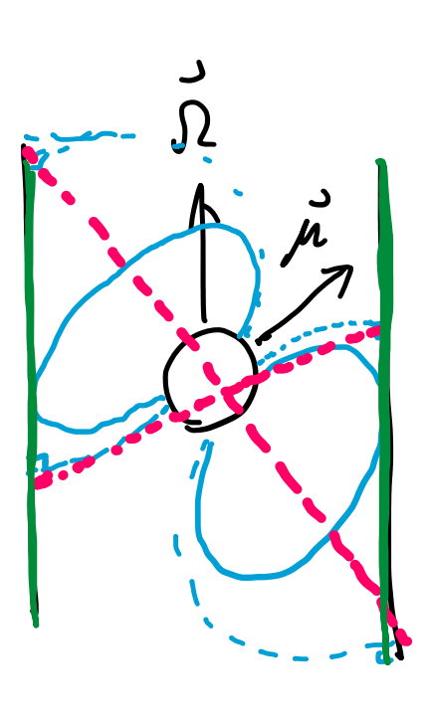
(or $\sigma_M = \frac{1}{\lambda}\left(\frac{W_{tot}}{W_A}\right)^{1/2}$, $W_A = \frac{m_e^2c^5}{e^2}$ ...)

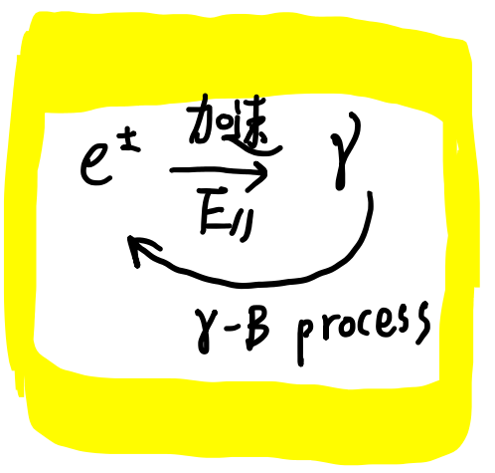
现在我们有了一些看起来比较靠谱且定量的基础理论, but how all this works?

(1.3) Rome (1973-1983)

first rigorous laws on
- secondary plasma generation
- magnetosphere structure
- wind
- ......

(a.) secondary plasma generation: we need $E_\parallel$





平衡磁层: $\rho = \rho_{GJ}$, $E_\parallel = 0$

对于 PSR 磁层, 三类主要的边界 ⇒ 可能容易偏离 ρ_{GJ}
① NS surface ② Light Cylinder
③ Zero charge surface

First model: inner gap (near ①)
Ruderman & Sutherland 1975 (RS 75)
Al'ber, Krotova & Éidman 1975

- Plasma outflow along open field lines
  ⇒ vacuum gaps formed above NS surface

⇑ Based on: ion ejection from NS forbidden
↕ (eject work function $A_W \sim 1$-5 keV)
"No supplement"

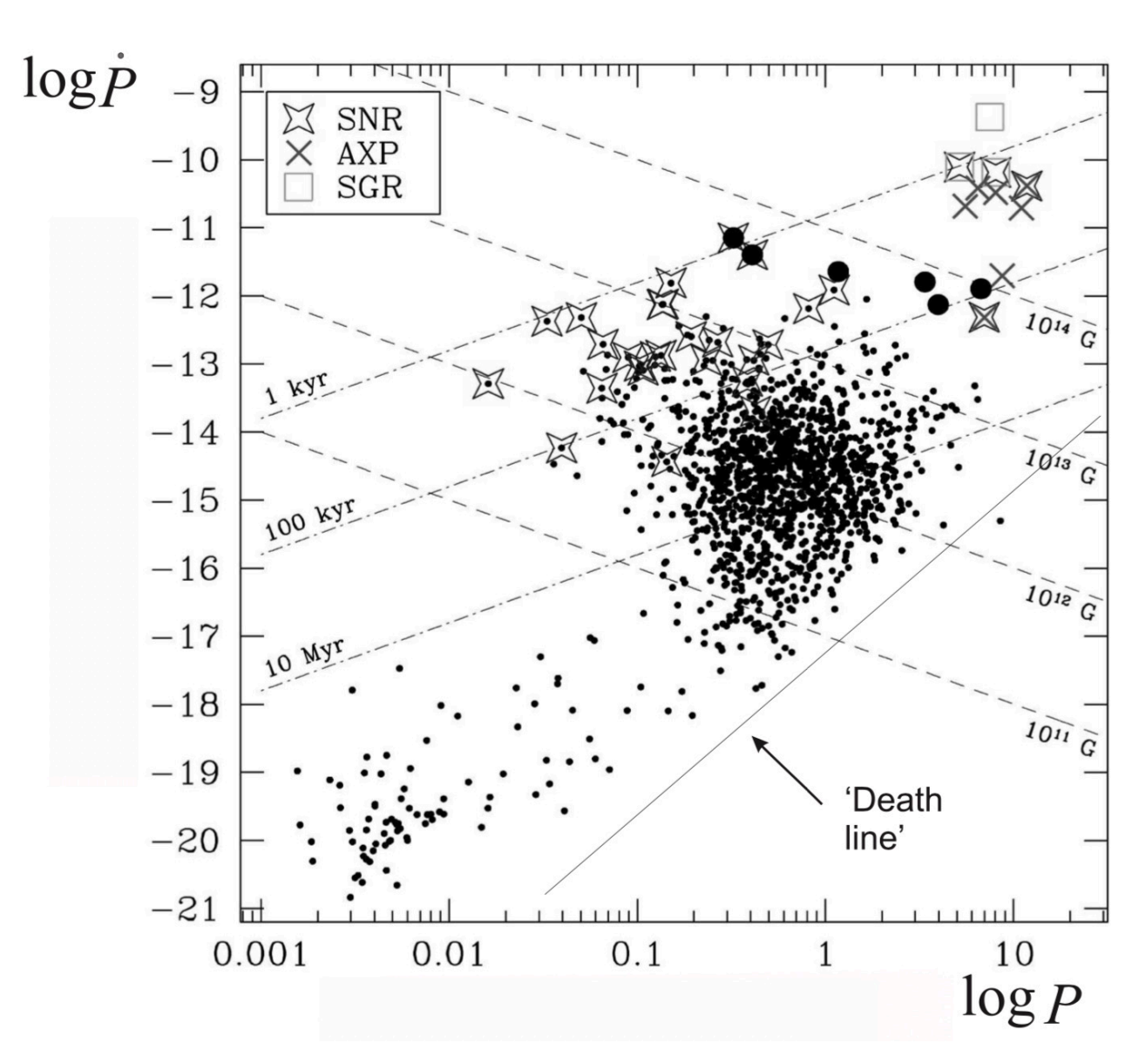
$E_\parallel$ ⇒ potential drop in a certain height
解 Poisson Eq (详见 RS1975 附录 III)
可知 Polar Cap 能产生的 maximum 电压:

$$\Delta V_{max} \simeq \frac{B_0R^3\Omega^2}{2c^2}$$

secondary plasma 所需:
$H_{RS} \simeq 10^4 B_{12}^{-4/7}P^{3/7}R_7^{2/7}$ (cm) ($R_7 = \frac{R_0}{10^7 cm}$ polarcap)
$\psi_{RS} \simeq 6\times10^{12} B_{12}^{-1/7}P^{-1/7}R_7^{4/7}$ (V)

"turn off": $\psi_{RS} = \Delta V_{max}$

(或 $H_{RS} = R_0$)



One question of RS: ion ejection forbidden?

Later estimation: $A_W \sim 100$ eV $\ll$ 1~5 keV for NS

替代方案: Fawler & Arons & Scharlemann 1977
Arons & Scharlemann 1979
......
free-flow ......

来不及推完了......

PSR Eq.
Current Problem
Wind Problem
PIC 时代 ...