Constraint on Pulsar Wind Properties from Induced Compton Scattering off Radio Pulses

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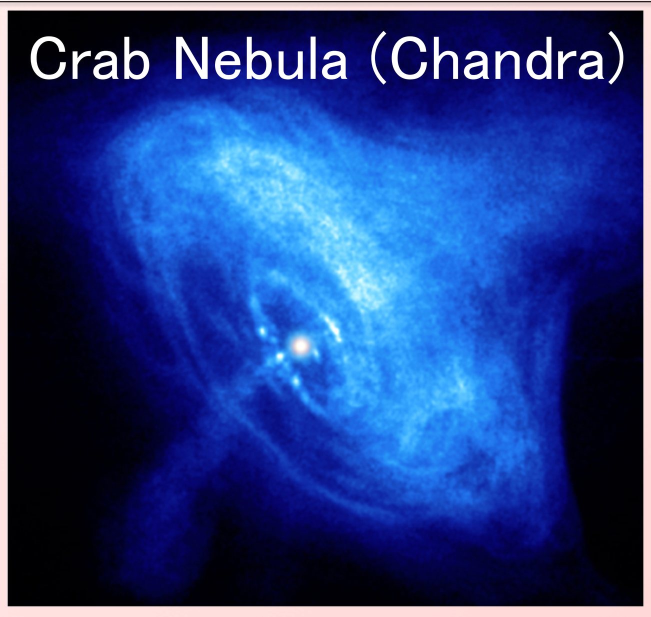
ABSTRUCT

see also Tanaka, S. J., & Takahara, F. 2013, PTEP, 123E01

We study induced Compton scattering by a relativistically moving cold plasma to constrain pulsar wind properties (the magnetization σ, the pair multiplicity κ & the bulk Lorentz factor γ). Because of high brightness temperature T_b of radio pulses ($T_b > 10^{26}$K for Crab), induced scattering would dominates spontaneous one. Relativistic effects cause a significant increase or decrease of the scattering coefficient depending on scattering geometry (inclination angle of the wind velocity with respect to the radio pulse θ_{pl} & the size of radio emission region r_e). Applying to the Crab pulsar ($\kappa\gamma(1+\sigma)=10^{10.5}$), $\theta_{pl} \sim 1$, $r_e \sim 10^3$cm & $\sigma \sim 1$ are required at the light cylinder to satisfy $\kappa > 10^{6.6}$ suggested by recent studies of the Crab Nebula.

I. Problems of Pulsar Wind



Young Rotation Powered Pulsars lose their rotational energy by pulsar winds.

$$L_{spin} \sim \kappa \dot{N}_{GJ} \gamma m_e c^2 (1+\sigma)$$

$\dot{N}_{GJ} \propto (L_{spin})^{1/2}$: Goldreich-Julian current

Only one stringent constraint

$$\kappa\gamma(1+\sigma) = 1.4 \times 10^{10} L_{spin,38}^{1/2}$$

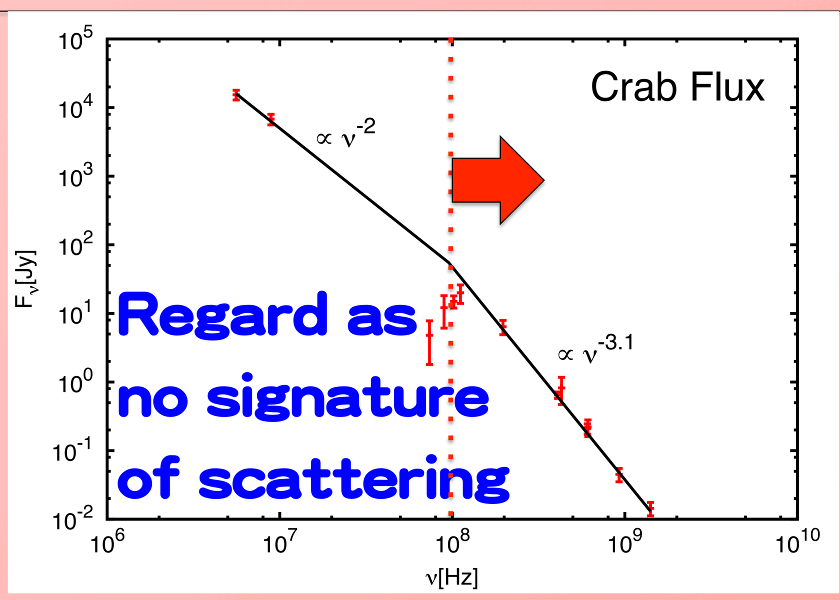
Studies of wind properties

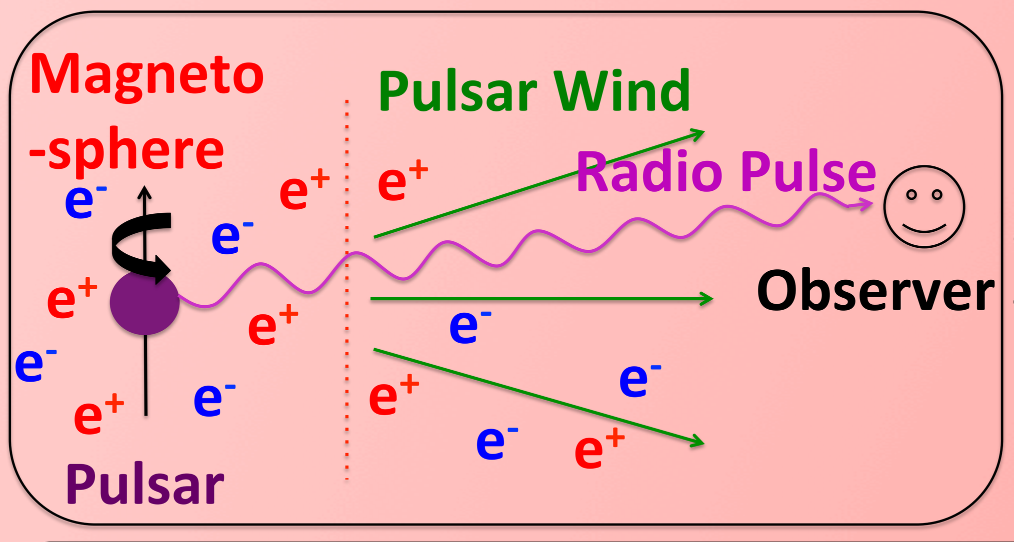
1. σ-problem:
   - $\sigma \ll 1$ ($\gamma \sim 10^6$, $\kappa \sim 10^4$) @ r_{TS} — Rees & Gunn74, Kennel & Coroniti84
   - $\sigma \gg 1$ inside r_{LC} — Goldreich & Julian69, Ruderman & Sutherland75
2. κ-problem:
   - $\kappa \gg 10^6$ (radio PWN emission) — ST & Takahara10, Bucciantini+11
   - $\kappa \sim 10^{4\text{-}5}$ (cascade simulations) — Daugherty & Harding82, Hibschman & Arons01

We do not achieve a consensus.

II. Constraint

Radio pulses go through wind plasma. Scattering optical depth for induced Compton scattering (ICS, see, §III) $\tau_{ICS}(10^8\text{Hz}) < 1$!



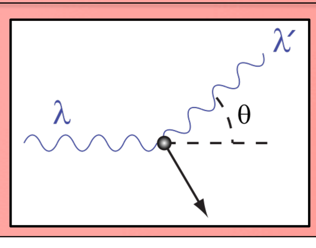


Like the compactness problem of GRB, large γ or small κ is required for escaping from ICS.

Constraint!

Wilson & Rees78 obtained $\gamma > 10^4$ or $\kappa < 10^6$ ($\sigma \sim 1$) for a special scattering geometry.

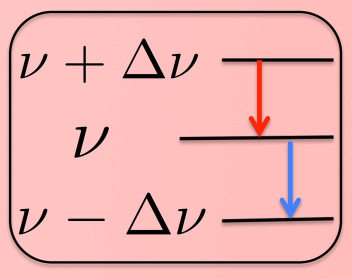
III. Induced Compton Scattering



Qualitative description ($e^\pm$ rest frame)

$$\frac{dn_{ph}(\nu)}{dt} \approx n_{pl}\sigma_T c[n_{ph}(\nu+\Delta\nu)(1+n_{ph}(\nu)) - n_{ph}(\nu)(1+n_{ph}(\nu-\Delta\nu))]$$

spontaneous + induced terms



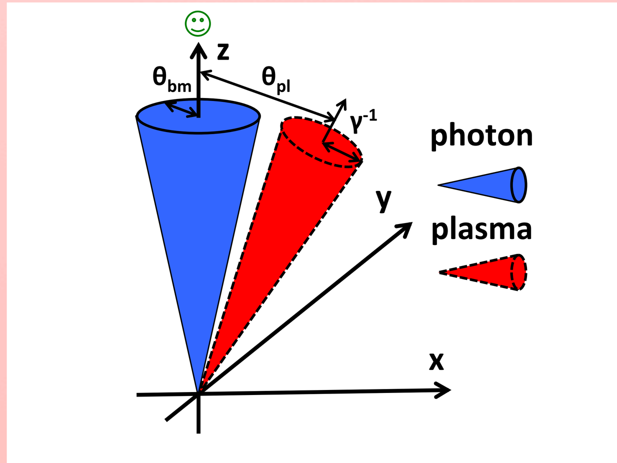
Photons always lose energy by scattering in $e^\pm$ rest frame.

$$\tau_{ICS}(\nu) \sim n_{pl}\sigma_T l \times \frac{k_B T_b(\nu)}{m_e c^2} \times (\Delta\Omega)^2$$

- $n_{pl}\sigma_T l$: Optical depth for Spontaneous scattering, $\tau_{spon} < 1$ @ light cylinder
- $\frac{k_B T_b(\nu)}{m_e c^2}$: Correction for induced process $>10^{15}$ @10^8Hz for Crab
- $(\Delta\Omega)^2$: Opening angle of radio beam. Estimated from pulse width.

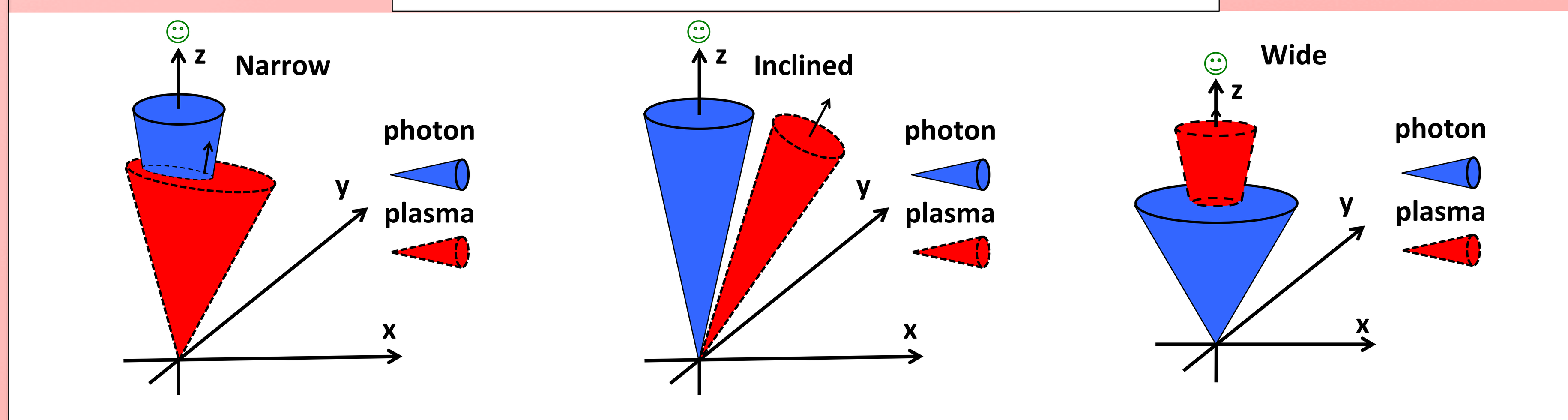
$\Delta\Omega$: pulse opening angle
n_{ph}: photon occupation number
σ_T: Thomson cross section
T_b: brightness temperature

IV. Application to Crab



- Wind density from spin-down power
  → $n_{e^\pm} = \frac{L_{spin}}{4\pi r^2 \gamma m_e c^3 (1+\sigma)}$ radial wind
- Beam opening angle
  → $\theta_{bm}(r) \approx \frac{r_e}{r}$ for $r > r_e$ $r_e \sim 10^3$ cm or 10^7 cm
- Brightness temperature
  → $\frac{k_B T_b(\nu)}{m_e c^2} = 1.7 \times 10^{16} \left(\frac{F_\nu}{\text{Jy}}\right)\left(\frac{d}{\text{kpc}}\right)^2\left(\frac{\nu}{100\,\text{MHz}}\right)^{-2}\left(\frac{r_e}{10^7\,\text{cm}}\right)^{-2}$

Scattering Geometries

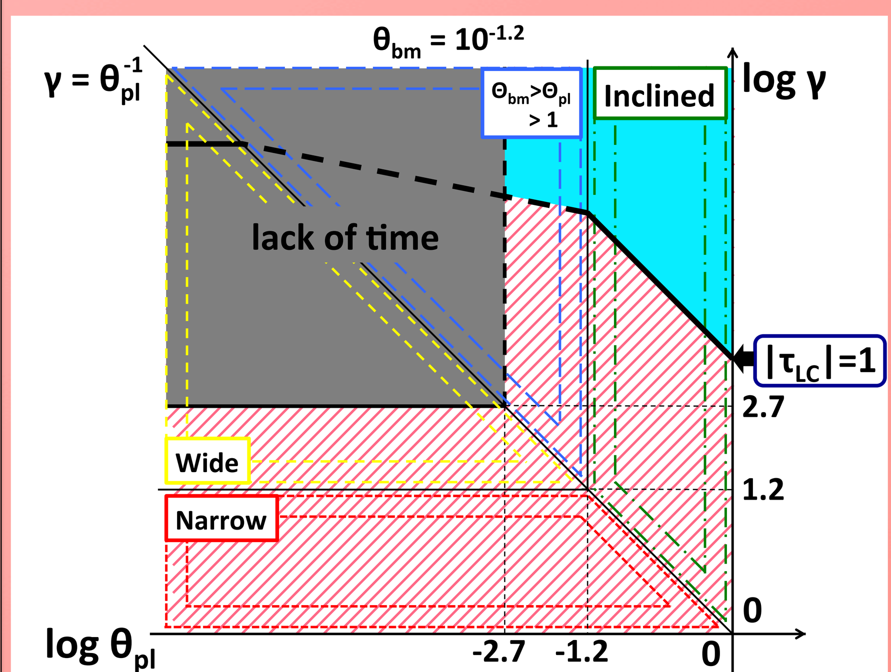


Only wind velocity (γ & θ_{pl}) is parameter

V. Results

Approximate form of τ_{ICS} in Obs. frame

$$\tau_{ind} \approx n_{pl}(r)\sigma_T r \frac{k_B T_b(\nu)}{m_e c^2} I(\theta_{bm}, \theta_{pl}, \gamma) \quad \text{with} \quad I_{Narrow} = \gamma\theta_{bm}^4,\ I_{Inclined} = \theta_{bm}^4/\theta_{pl}^4,\ I_{Wide} \approx 1$$



τ_{ICS} on γ-θ_{pl} plane @ light cylinder for example

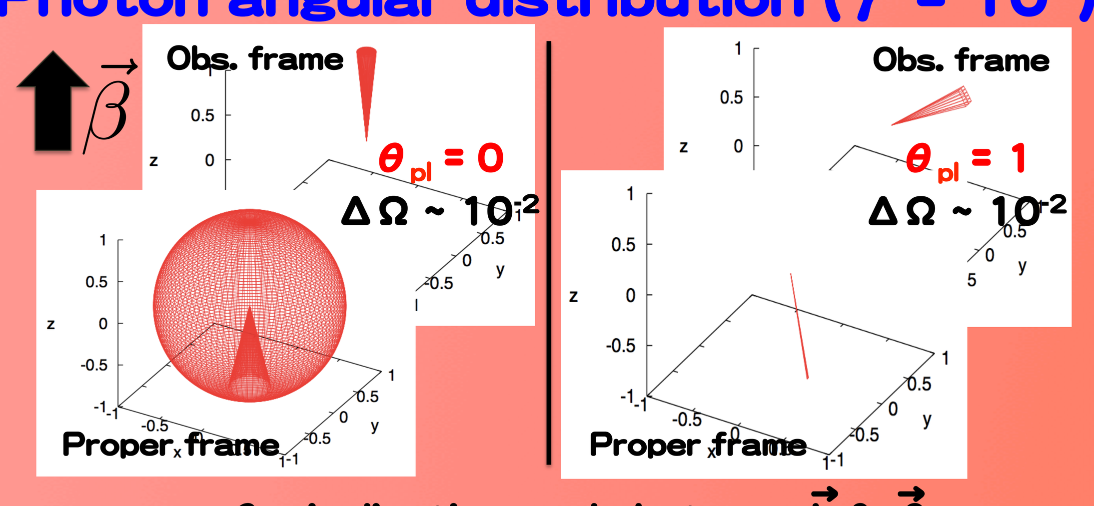
Blue region: $\tau_{ICS} < 1$
Red region: $\tau_{ICS} > 1$
Gray region: no scattering by "lack of time" effect
Normal treatment of scattering breaks down when $\lambda > r$ in proper frame.

Geometry	r_e	θ_{pl}	γ	κ
Inclined	10^7cm	~1	$>10^{3.7}(1+\sigma)^{-0.25}$	$<10^{6.8}(1+\sigma)^{-0.75}$
Aligned	10^7cm	0	$>10^{4.2}(1+\sigma)^{-0.1}$	$<10^{6.2}(1+\sigma)^{-0.9}$
Inclined	10^3cm	~1	$>10^{1.7}(1+\sigma)^{-0.25}$	$<10^{8.8}(1+\sigma)^{-0.75}$
Aligned	10^3cm	0	$>10^{3.4}(1+\sigma)^{-0.1}$	$<10^{7.1}(1+\sigma)^{-0.9}$

We conclude
- $\theta_{pl} \sim 1$ is required for large κ ($\gg 10^6$).
- $\sigma \ll 10^4$ @ r_{LC} is also required for $\kappa > 10^6$
- Larger κ is allowed for small r_e

An example of relativistic effects (light aberration)

Photon angular distribution ($\gamma = 10^2$)



θ_{pl}: inclination angle between $\vec{k}$ & $\vec{\beta}$

Photon angular distribution in $e^\pm$ rest frame is significantly different for the scattering geometries in Obs. frame.

In addition, Doppler effect & Lorentz contraction which also depend on the scattering geometry in Obs. frame should be considered.

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