A Stochastic Acceleration Model of Radio Emission from Pulsar Wind Nebulae

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ABSTRACT

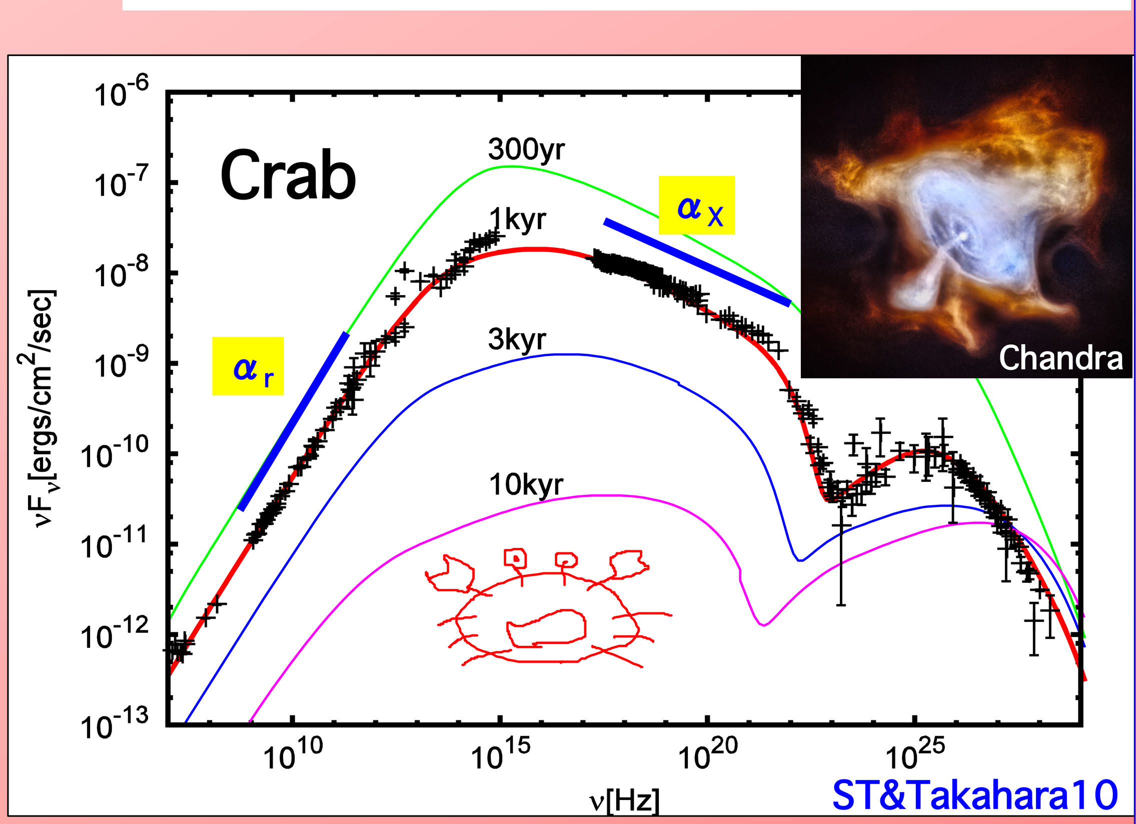
The Pulsar Wind Nebulae (PWNe) spectra are described by non-thermal emissions from $e^{\pm}$s whose the energy distribution is not reproduced by standard shock particle acceleration and cooling processes. For example, a broken power-law energy distribution is adopted, groundlessly. Here, we study a stochastic acceleration for the radio emitting particles by a turbulence inside PWNe. We upgrade our one-zone spectral evolution model and apply to the Crab Nebula. We consider the both continuous and impulsive injections of particles to the acceleration process. Time dependent the particle injection and/or the momentum diffusion coefficient are required to reproduce the radio observations.

I. Spectrum of PWNe

Spectral indices at radio (α_r) & X-rays (α_X) is different.
<= not explained by a single PL injection.

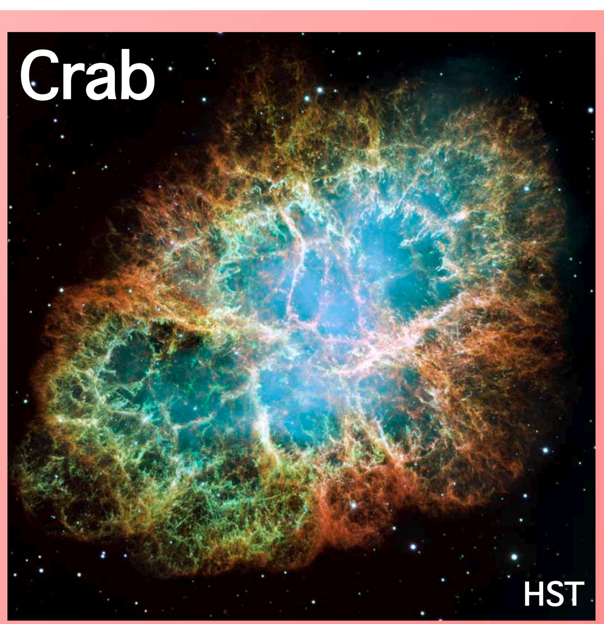
Object	$\Delta\alpha = \alpha_r - \alpha_x$
Crab	0.8
3C58	0.9
G21.5-0.9	1.2

$\Delta\alpha > 0.5$ is difficult

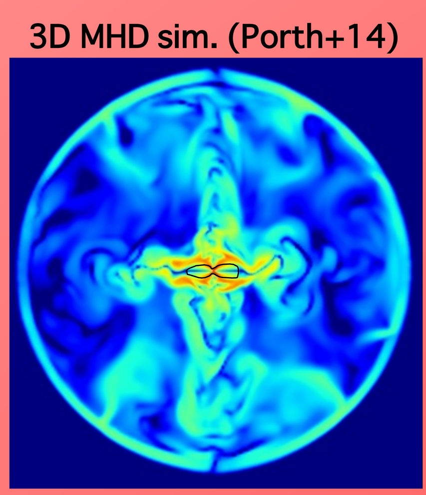


May not be the same origin, relic particles?

II. Turbulences in PWNe



Interaction with SN ejecta & anisotropic pulsar winds cause turbulence in PWNe.



Stochastic particle acceleration expected.

III. One-zone Model

Fokker-Planck equation

$$\frac{\partial}{\partial t}N(\gamma,t) + \frac{\partial}{\partial \gamma}\left[\left(\dot{\gamma}_{\rm cool}(\gamma,t) - \gamma^2 D_{\gamma\gamma}(\gamma,t)\frac{\partial}{\partial\gamma}\frac{1}{\gamma^2}\right)N(\gamma,t)\right] = Q_{\rm PSR}(\gamma,t) + Q_{\rm ext}(t)$$

$$\dot{\gamma}_{\rm cool}(\gamma,t) = \dot{\gamma}_{\rm ad}(\gamma,t) + \dot{\gamma}_{\rm syn}(\gamma,t) + \dot{\gamma}_{\rm IC}(\gamma,t)$$

$$\frac{4\pi}{3}R^3(t)\frac{B^2(t)}{8\pi} = \eta_{\rm B}\int_0^t L_{\rm spin}(t')dt'$$

Same as ST&Takahara10

$$Q_{\rm PSR}(\gamma,t) \propto \gamma^{-p},\ (\gamma_{\rm min} \le \gamma \le \gamma_{\rm max})$$

$$\int d\gamma Q_{\rm PSR}(\gamma,t)\gamma m_e c^2 d\gamma = (1-\eta)L_{\rm spin}(t)$$

Single PL injection from PSR for X-ray emitting particles

Momentum diffusion coefficient
q = 5/3 (Kolmogorov) or 2 (hard-sphere approx.)
t_{accel}: parameter of turbulence
t_{decay}: parameter of turbulence

$$D_{\gamma\gamma}(\gamma,t) \equiv \frac{\gamma_{\rm min}^2}{2t_{\rm accel}}\left(\frac{\gamma}{\gamma_{\rm min}}\right)^q \exp\left(-\frac{t}{t_{\rm decay}}\right)$$

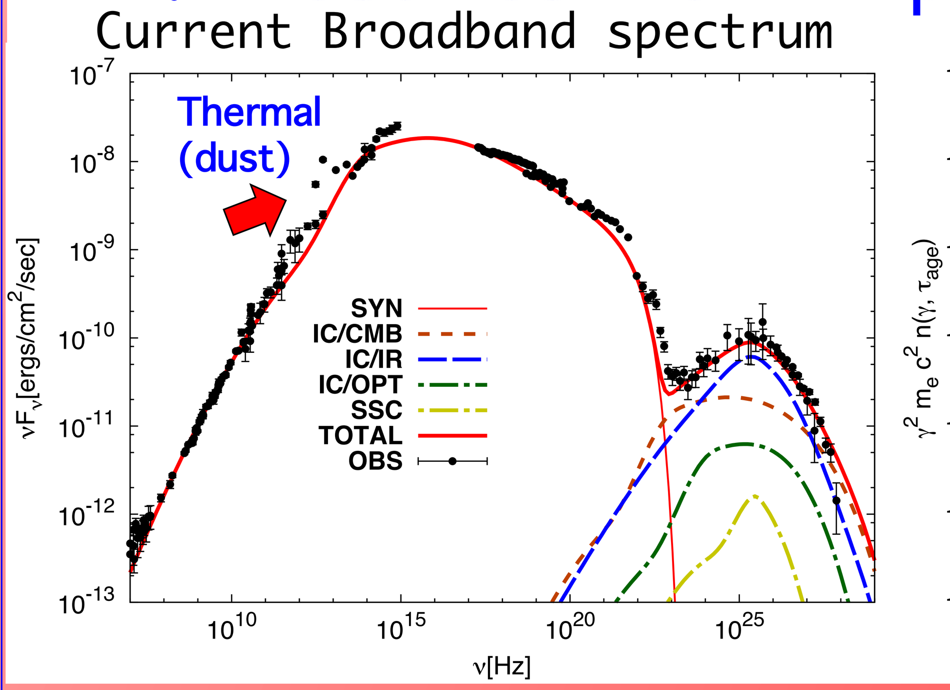
$$Q_{\rm ext}(t) = N_{\rm ini}\delta(t-t_{\rm ini}) + Q_{\rm ej}\left(\frac{t}{t_{\rm age}}\right)^s$$

Relic particles N_{ini}: impulsive injection at $t_{ini} << t_{age}$.
Ejecta particles Q_{ej}: injected continuously (power-law) from filaments or the contact surface.

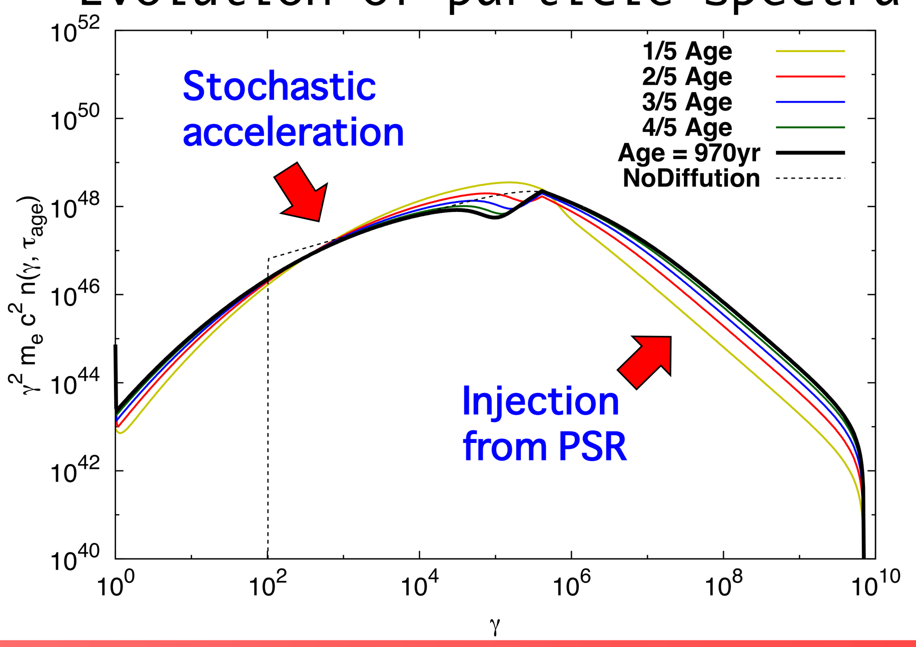
γ_{min} = 4×10^5, γ_{max} = 7×10^9, η_B = 5×10^{-3} ($\eta = \eta_B + \eta_{turb}$) are common.

IV. Results for Impulsive Injection

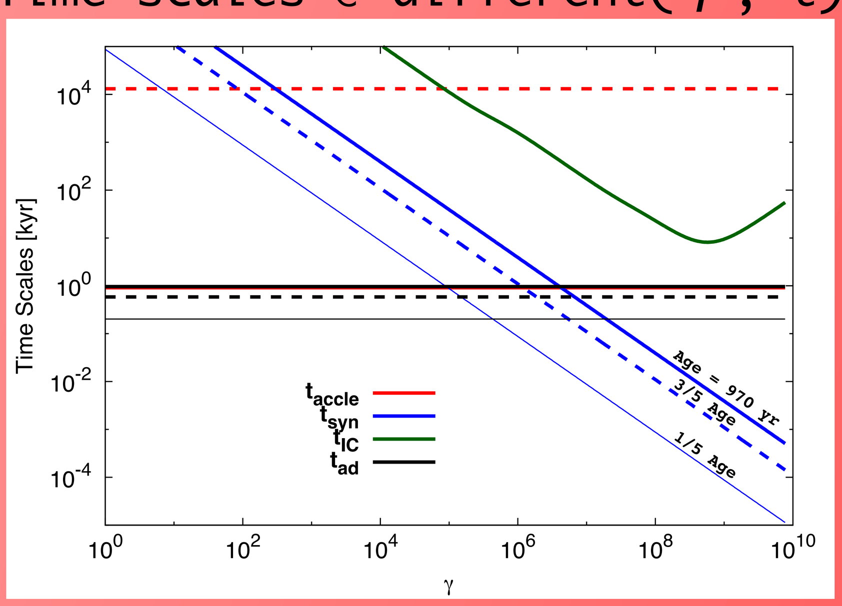
Current Broadband spectrum



Evolution of particle spectra



Time-scales @ different(γ, t)



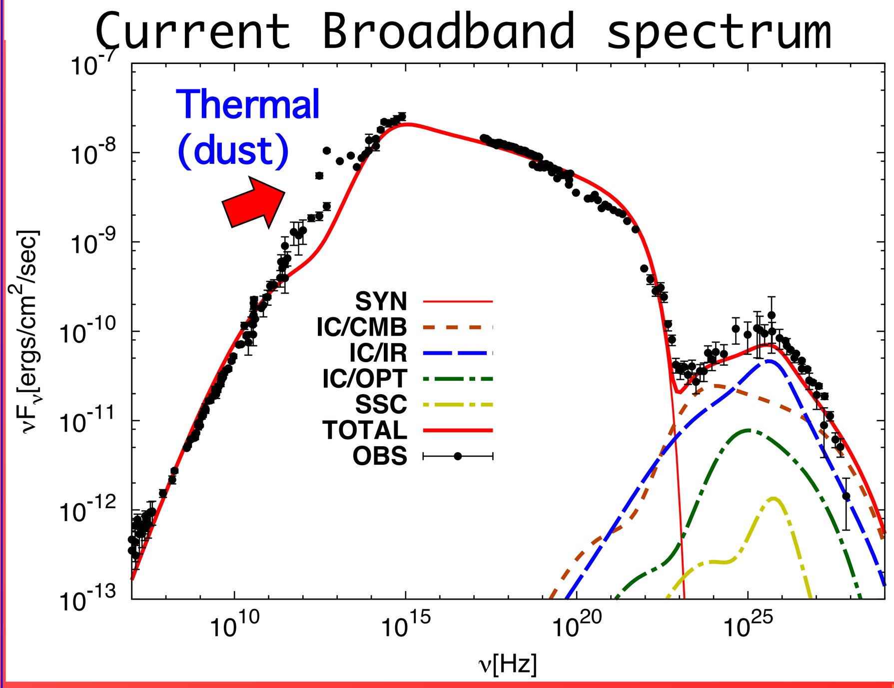
	value
p	2.5
1-η	0.6
q	2
t_{accel}	5.5yr
t_{decay}	40yr
N_{ini}	1.7×10^{51}
Q_{ej}	0
s	-

η_{turb} = 0.4
hard-sphere

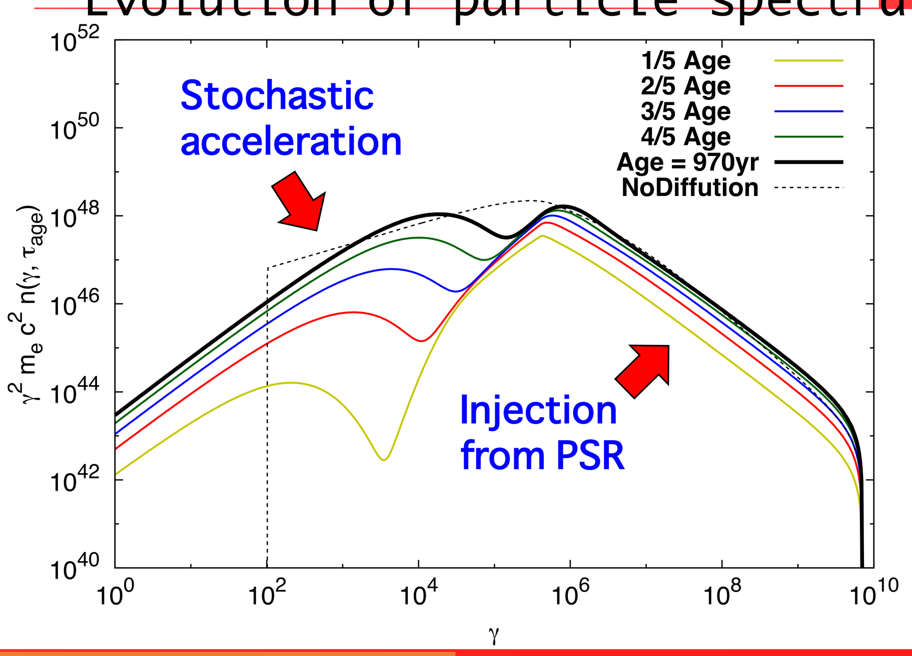
N_{tot} = 2.8×10^{51} for TT10

V. Results for Continuous Injection

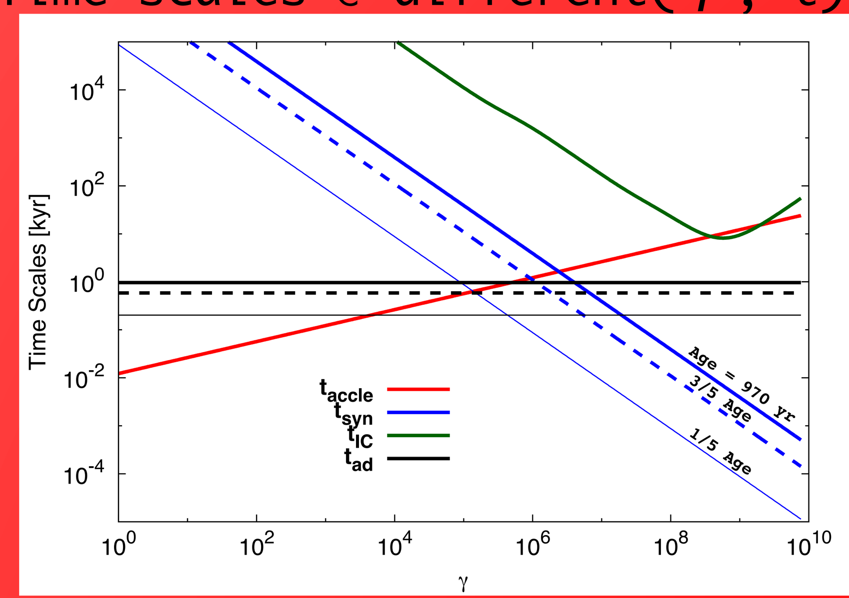
Current Broadband spectrum



Evolution of particle spectra



Time-scales @ different(γ, t)



	value
p	2.3
1-η	0.3
q	5/3
t_{accel}	900yr
t_{decay}	∞
N_{ini}	0
Q_{ej}	$3\times10^6 \dot{N}_{GJ}$
s	2

η_{turb} = 0.7
Kolmogorov

$Q_{PSR} = 1.4\times10^4 \dot{N}_{GJ}$
$Q_{ej} \propto \rho_{ej} v r^2 \propto t^2$

VI. Discussion & Conclusions

Model of stochastic acceleration origin for radio emitting particles is demonstrated!

- Impulsive: decaying turbulence + hard-sphere approx.
- Continuous: Increasing injection + Kolmogorov spectrum
- Stochastic acceleration (turbulence) needs to be energetically significant amount of spin-down power.

6-11, Jun. 2016, Supernova Remnants: An Odyssey in Space After Steller Death @ Chania, Crete, Greece