Dynamics of Pulsar Wind Nebula with Magnetic Dissipation and Turbulence

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ABSTRACT

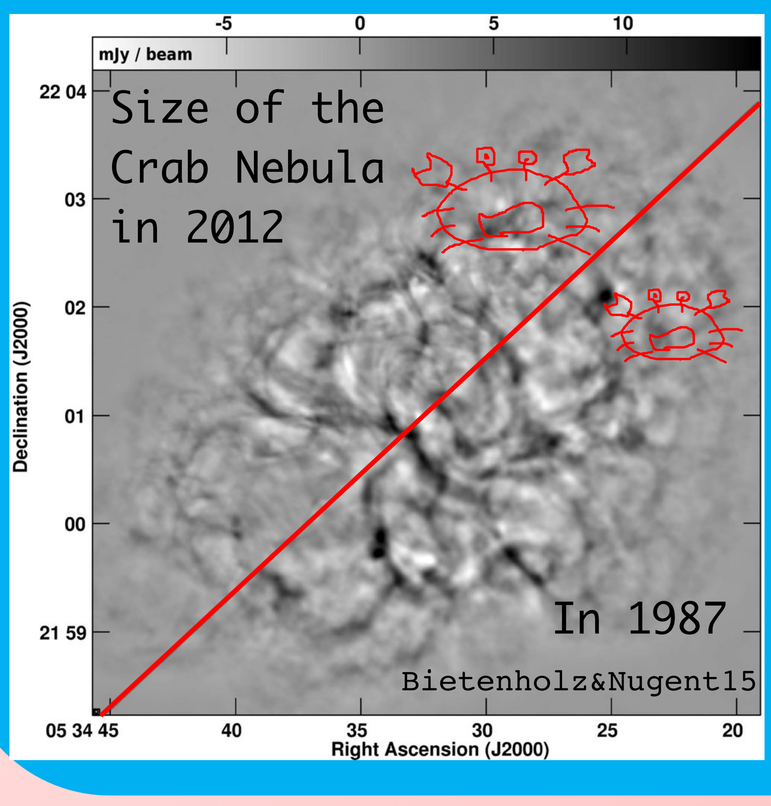
Pulsar wind nebulae (PWNe) are composed of relativistic magnetized plasma wind supplied from their central pulsars, called pulsar wind. Based on standard ideal magnetohydrodynamics model of PWN, magnetization of the pulsar wind is much less than unity in order to explain the observed slow expansion of the PWN. On the other hand, the pulsar wind is Poynting dominated at its base. This is called σ-problem. Here, we introduce our recent study extending the standard ideal MHD model by Kennel & Coroniti. Including the effects of magnetic dissipation and turbulence, requirement of low-magnetization from the dynamics of PWNe is relaxed.

I. σ-problem in PWNe

$$\sigma \equiv \frac{\text{Poynting flux}}{\text{Plasma energy flux}}$$

Pulsar winds are a high-σ flow at their origin, i.e., pulsar magnetosphere, while they seem to be a low-σ flow at their end, i.e., termination shock or PWN.

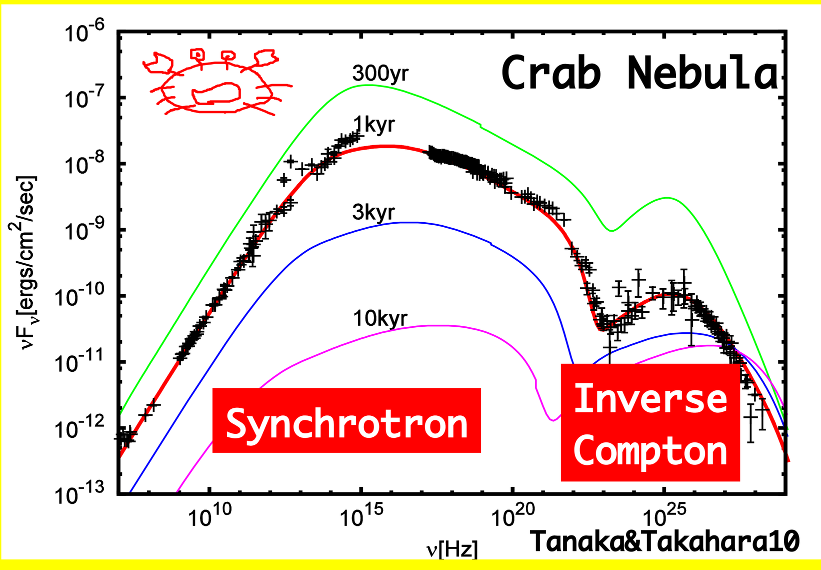
σ-problem from dynamical properties



Observed expansion velocity of the Crab Nebula v_{Crab} of ~ 1,500 km/s is much slower than speed of light *c*.

v_{Crab} / *c* ~ σ from the standard model by Kennel & Coroniti, i.e., we require σ ≪ 1.

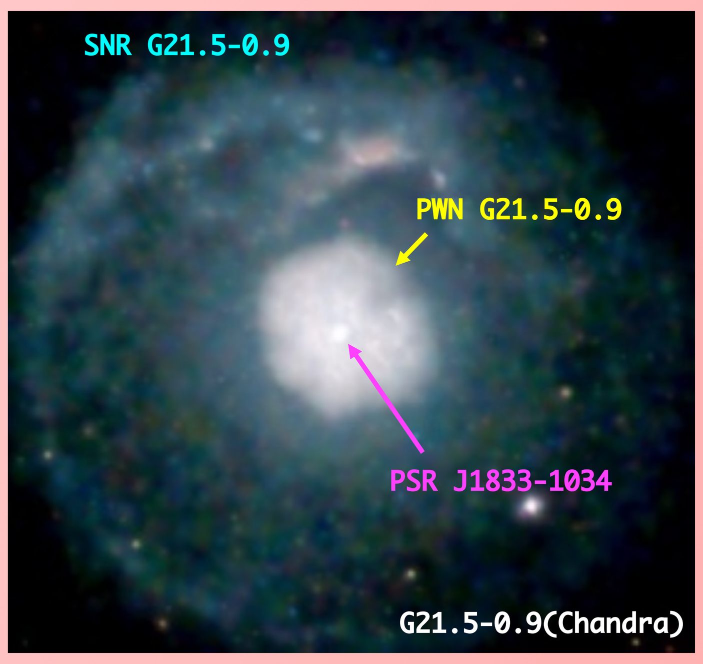
σ-problem from spectral properties



Observed broadband spectrum of the Crab Nebula is explained by a emission from low-σ plasma (synchrotron + inverse Compton scattering model).

We focus on dynamical σ-problem here.

II. Model of Kennel & Coroniti(1984)



① Cold e± plasma from pulsar
② Standing termination shock
③ Steady and spherical system
④ Pure radial outflow
⑤ Pure toroidal B-field
⑥ Ideal MHD approximation

We discard the above approx. ⑤ & ⑥.

V. Further Studies

① Broadband brightness & polarization profiles of PWNe, i.e., solving spectral σ-problem simultaneously).
② More realistic formulation of the non-ideal MHD terms.
③ Relating with a stochastic acceleration model of radio-emitting particle developed by Tanaka & Asano (2017).

III. Model

We extend KC model including the three non-ideal MHD effects.
Tanaka,Toma&Tominaga(2018)

① Conversion from toroidal to turbulent B-field
② Dissipation of turbulent B-field
③ Radiative (synchrotron) loss of plasma heat

$$\langle \nabla_\mu (n u^\mu) \rangle = 0, \quad \text{Eq. of continuity}$$

$$\langle \nabla_\mu T^{\mu t} \rangle = -\gamma \frac{\Lambda_{\rm rad}}{c}, \quad \text{Conservation of total energy}$$

$$-\langle u_\nu \partial_\mu T^{\mu\nu}_{\rm FL} \rangle = \frac{\delta b^2/2}{\tau_{\rm diss}} - \frac{\Lambda_{\rm rad}}{c}, \quad \text{Conservation of fluid internal energy}$$

$$\frac{1}{2}\langle \bar{b}_\mu e^{\mu\nu\alpha\beta} \nabla_\nu F_{\alpha\beta} \rangle = -\frac{\bar{b}^2/2}{\tau_{\rm conv}},$$

$$\frac{1}{2}\langle \delta b_\mu e^{\mu\nu\alpha\beta} \nabla_\nu F_{\alpha\beta} \rangle = \frac{\bar{b}^2/2}{\tau_{\rm conv}} - \frac{\delta b^2/2}{\tau_{\rm diss}}.$$

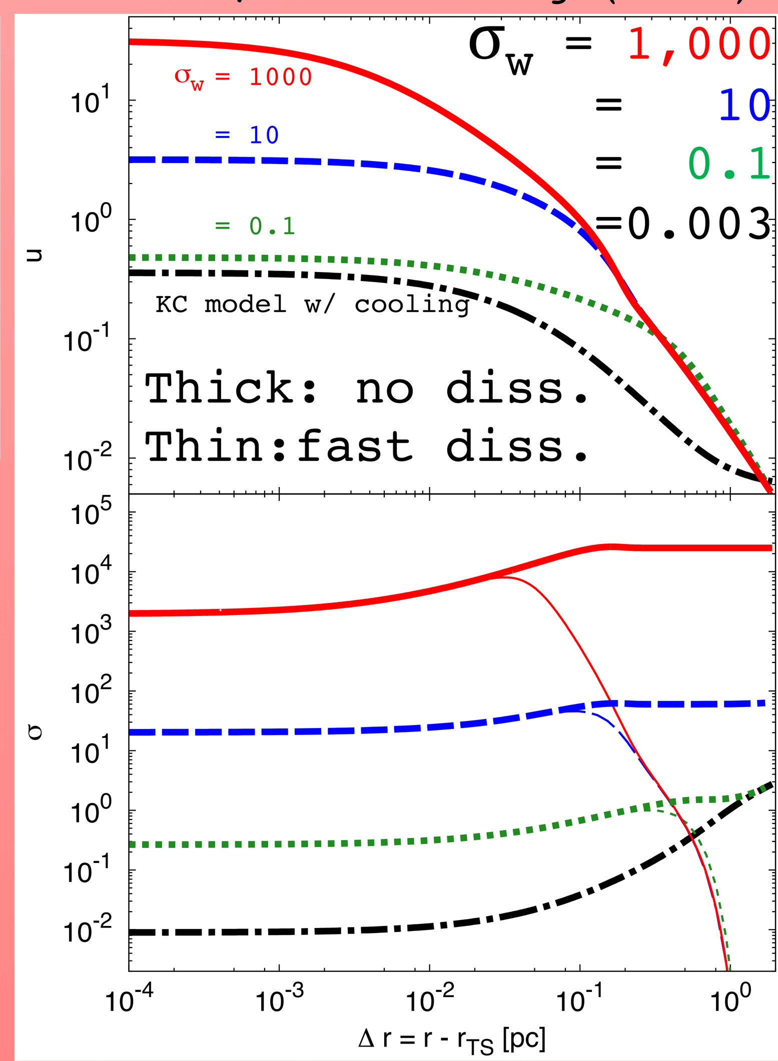
Induction equation for (mean) toroidal field + turbulent field

- Steady & spherical symmetry
- Relativistically hot plasma (Eq. of state)
- Five variables (*n, h, p, u,* b^2, δb^2)
- Omitting all the RHS terms, KC model is recovered.
- $\Lambda_{\rm rad}$, $\tau_{\rm diss}$, $\tau_{\rm conv}$ are the parameters of the system.

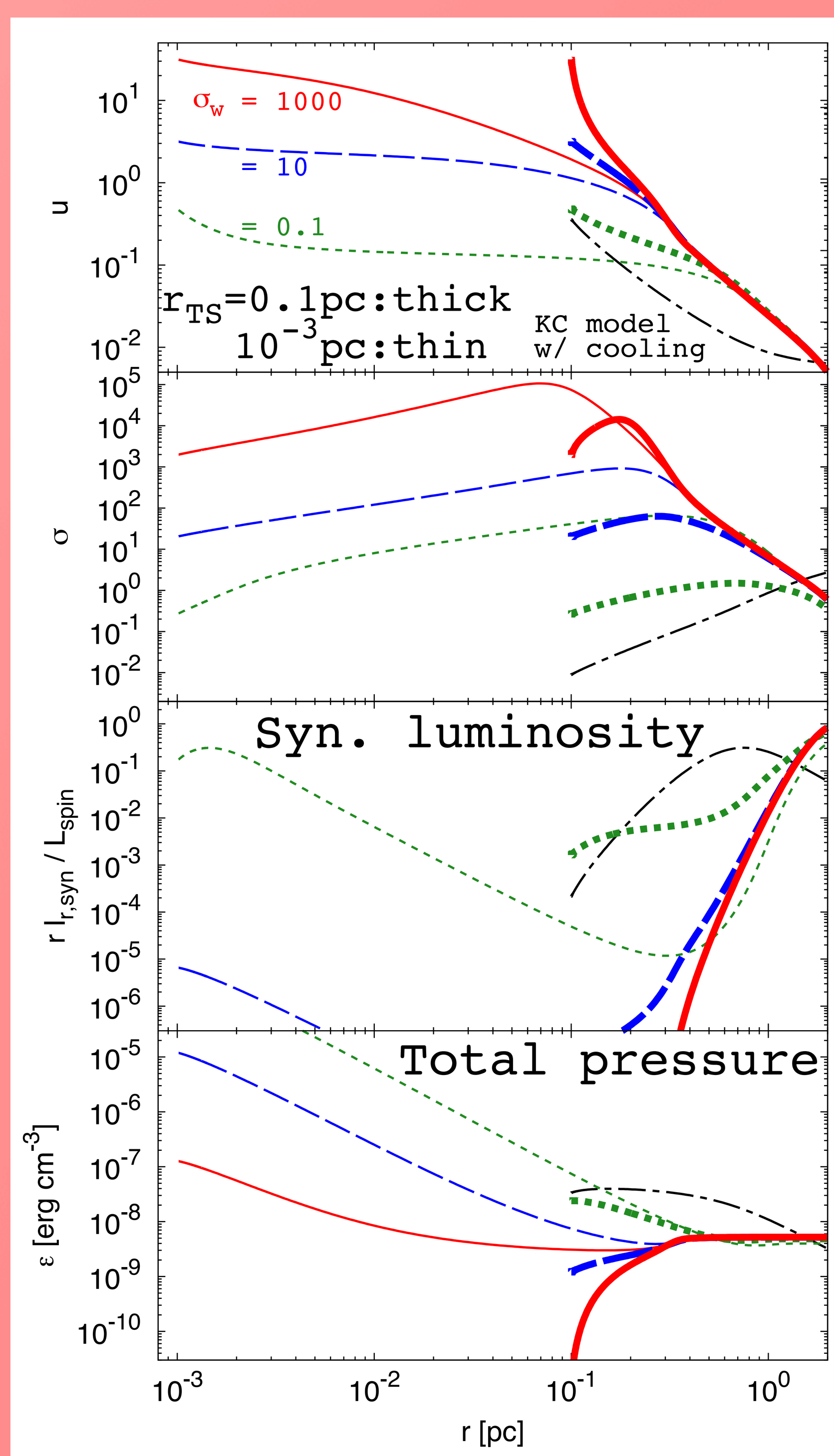
VI. Results

Applying the model to the Crab Nebula
Tanaka,Toma&Tominaga(2018)

	Adopted				Derived	
$\sigma_{\rm w}$	$\kappa_{\rm w}$	$r_{\rm TS}$(pc)	$\tau_{\rm diss}$(yr)	$\tau_{\rm conv}$(yr)	$t_{\rm adv}$(kyr)	$\eta_{\rm syn}$
Fig. 1						
10^3	10^4	0.1	10	0.228	0.434	0.0260
10	–	–	10	0.308	0.433	0.0259
0.1	–	–	10	6.51	0.435	0.0370
10^3	–	–	∞	0.223	0.435	$<10^{-3}$
10	–	–	∞	0.301	0.434	$<10^{-3}$
0.1	–	–	∞	7.56	0.404	0.167



Other than KC model, a finite $\tau_{\rm conv}$ (typically, months to years) is required for v_{Crab} ~ 1,500km/s



- $r_{\rm TS}$ = 0.1 pc is “not” the necessarily condition for v_{Crab} ~ 1,500km/s because the MHD post-shock flow is not spatially isobaric.
- Radial brightness profile would distinguish models, i.e., syn. luminosity strongly depends on $\tau_{\rm conv}$, $\tau_{\rm diss}$, & $r_{\rm TS}$.

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