The Crab Nebula:
3-D modeling

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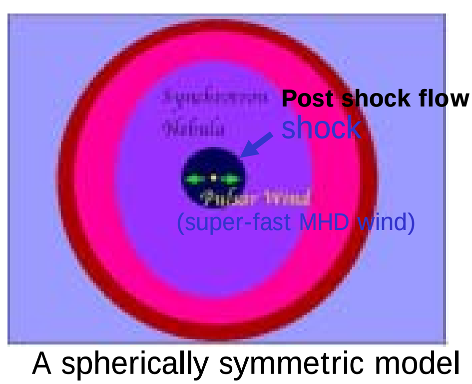
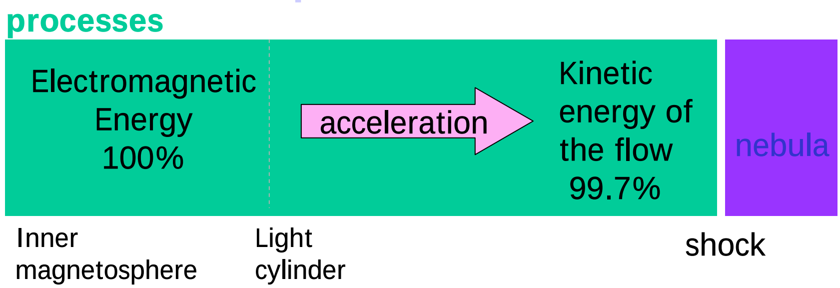
A standard picture of the Crab Nebula



A spherically symmetric model
(Kennel and Coroniti 1984)

KC model

- **Energy of the wind is conveyed not by electromagnetic field but by kinetic energy in bulk motion of the plasma outflow**



Parameters of the Pulsar Wind

L_w : Luminosity ∼ L_rot

3.3x10^6 — γ_w : Lorentz factor

3.8x10^{-3} — σ := **Electromagnetic energy flux / Kinetic energy flux**

0.38mG — P_N : confining pressure (B_eq = $(4\pi P\_N)^{1/2}$)

→ Synchrotron spectrum

Given L_sy=2x10^{37}erg/sec, R_N=0.6pc, peak and turn-off energy of the synchrotron spectrum, 2eV and 10^8eV, it is straightforward to deduce …

Fitting to the synchrotron spectrum
(whole nebula)

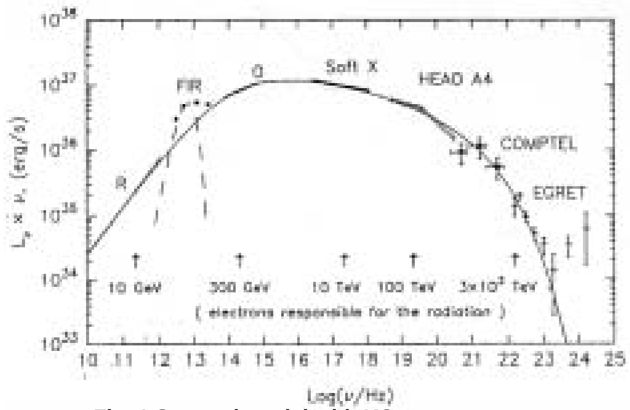
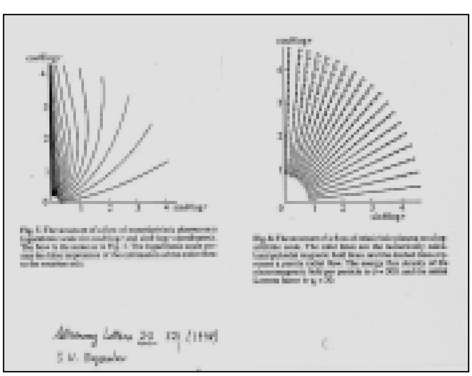
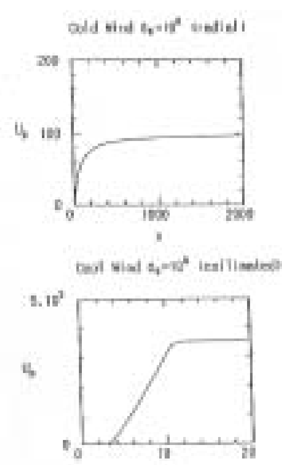


Fig. 1 Spectral model with KC parameters.
(Atoyan & Aharonian, 1996).

The smallness of **σ** is a mystery.

(dominance of the
kinetic energy over the
magnetic energy)





Chandra Observation

-Disc-jet structure
-Moving wisps

Wisp velocity 0.4-0.5 c

-Spatially resolved spectra

The kinetic-energy dominant wind shocks and shines

Mori 2002

Pulsar Nebula Project; 3D model

- High spatial resolution of Chandra enables us to examine the assumptions
  - •The ideal-MHD (frozen-in) condition in the nebula flow
  - •Toroidal field approximation

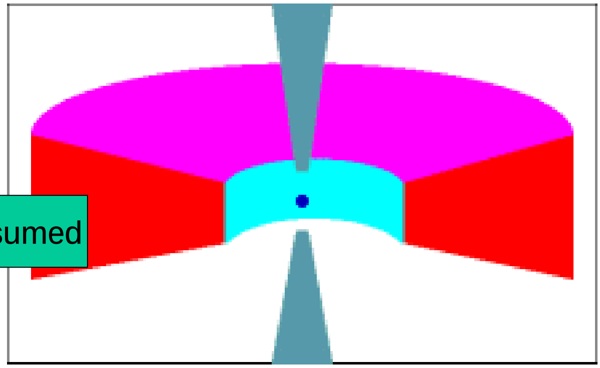
  which are used in the KC model but has not been checked before.
- Detailed investigation of the 3D structure of the nebula, e.g., spatially resolved spectra.

A 3D model

KC model

but

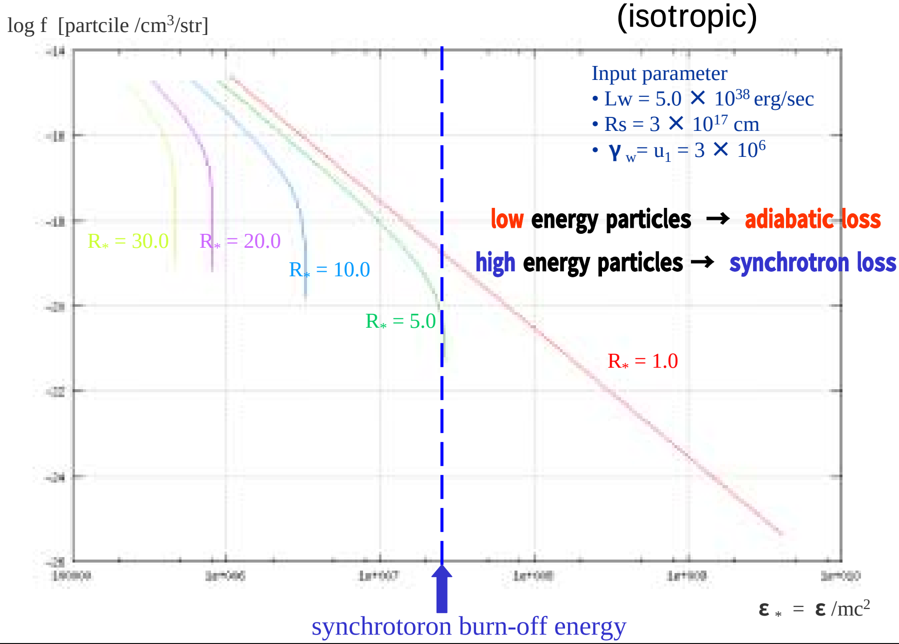
Disc wind is assumed



- Ideal-MHD (frozen-in) condition holds
- Toroidal field approximation

Evolution of the distribution function

(isotropic)



Volume emissivity j'

θ ′ is the pitch angle of the particle whose emission directs to the observer

$$j'(\theta', \omega') = \int_0^\infty \mathcal{P}_{s1}(\omega', \theta', \gamma) f(\gamma, \theta') \mathrm{d}\gamma$$
$$= 2\sigma_T c U_{\mathrm{mag}} \sin^2 \theta' \int_0^\infty \gamma^2 f(\gamma, \theta') \delta(\omega' - \omega_c) \mathrm{d}\gamma$$

Doppler boost

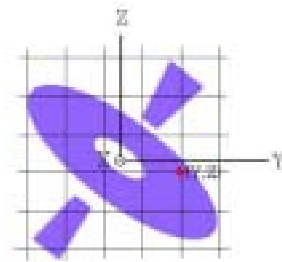
➡ $$j_\omega(\mathbf{n}_{\mathrm{obs}}) = \frac{1}{\Gamma^2 (1 - \beta\mu)^3} j'(\theta', \omega') \qquad \omega' = \Gamma(1 - \beta\mu)\omega$$

Intensity

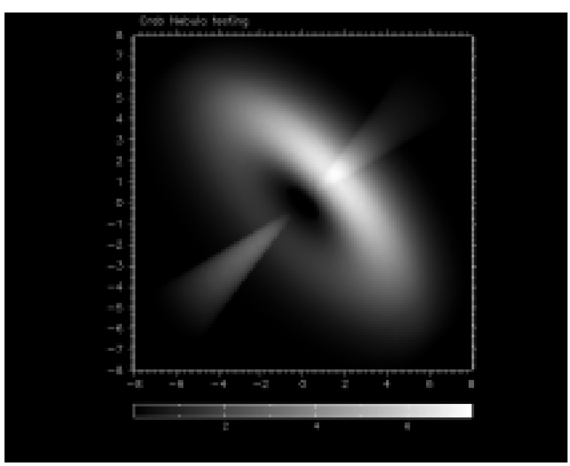
YZ plane = sky coordinate

$$I_\omega(Y, Z, \omega) = \int_{-X_{\max}}^{X_{\max}} j_\omega(\omega, R) dX$$

$$R = (X^2 + Y^2 + Z^2)$$



One may expect …



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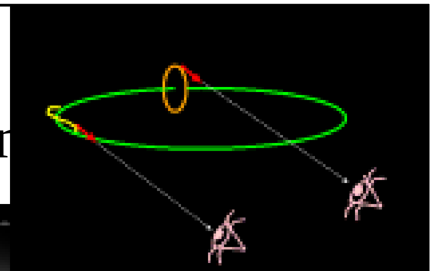
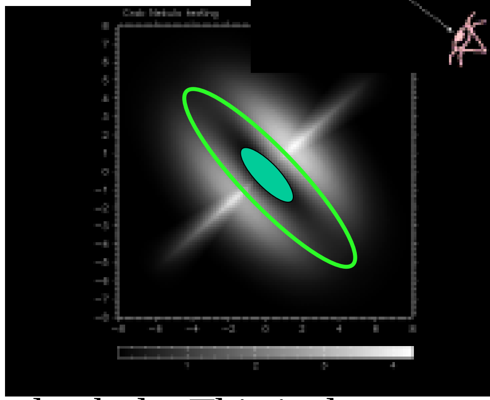


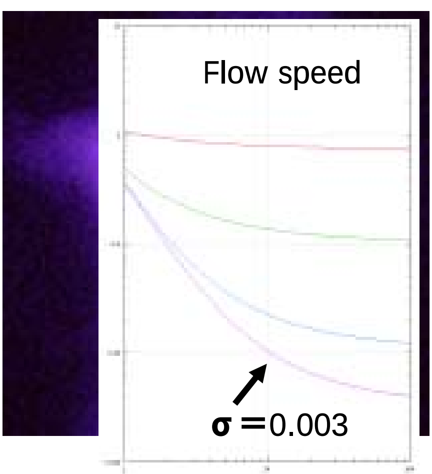


We suggest
Turbulent field
as large as the toroidal
component

- Lip-shaped nebula. This is due to pure toroidal field (pitch angle effect)

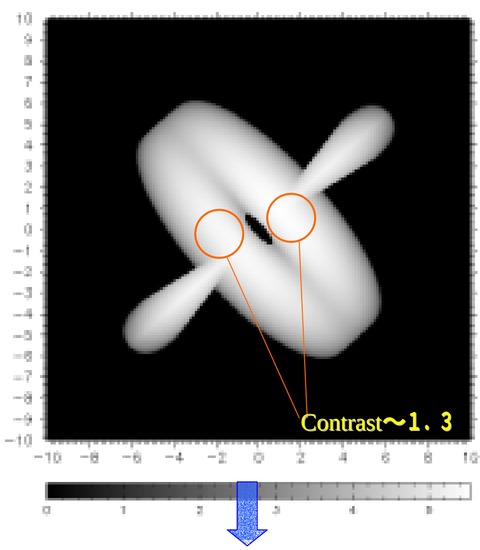
back-fore contrast (0.1-10.0 keV)

(Weisskopf et al.2000)



We need **~0.2 c**

Reproduced image

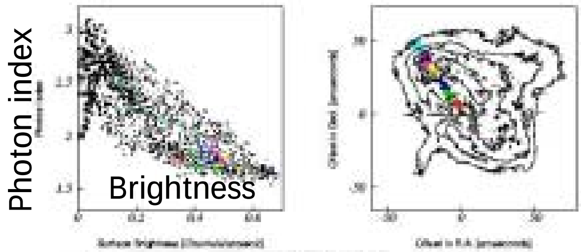


flow with σ =0.003, v**~0.048 c**

Reproduction of Spatially Resolved Spectra

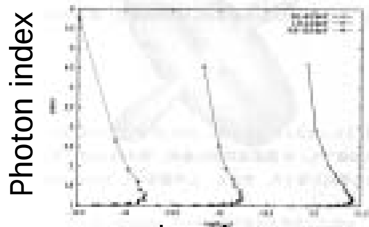
Chandra observation

(Mori 2002)



3D KC model

(present work)



Conclusion

- A simple extension of the KC model to 3D is made for comparison with Chandra observation.
- On one hand, reproduced spatially resolved spectra are in agreement with observation.
- On the other hand, reproduced image is lip-shaped suggesting disordered field ; some dissipation (non-ideal MHD), and
- contrast between back and fore sides is not reproduced, (if Doppler boost), **σ** may be larger (note v=0.45c for wisps.

Discussion

- We suggest that the ideal-MHD (frozen-in) condition is broken down in the nebula, e.g. by magnetic reconnection; magnetic field may be turbulent.
- If so, the post shock flow is faster (σ can be larger), particles are heated and accelerated not only at the shock but also in a larger region in the nebula.
- There should be some indication in the spatial resolved spectra; we will make a much detailed study in a subsequent paper.