The Crab Nebula: a theorist’s perspective

Alice K. Harding (NASA/GSFC)
Crab nebula
- Remnant from 1054 AD supernova at 2 kpc
- Young energetic pulsar powers pulsar wind nebula (Pacini 1967)
- Standard reference in X-rays and VHE gamma rays

Termination shock radius
Wind pressure = Nebular pressure

\[
\frac{\dot{E}_{sd}}{4\pi c R_S^2} \approx \frac{\dot{E}_{sd} \tau}{4\pi \frac{3}{\pi} R_N^3} \Rightarrow R_S \approx 3 \times 10^{17} \text{ cm}
\]

Rees & Gunn (1974)
First Synchrotron-self Compton models of the Crab Nebula

Gould 1965 – uniform B, Thomson $\sigma_C$

$J(\varepsilon) = \frac{1}{4\pi d^2} \int dV \int d\gamma n_e(\gamma) \int d\nu n_{ph}(\nu) \sigma_C(\gamma, \nu)$

• Volume integral – assumed spherical
• Electron spectrum – derived from observed synchrotron spectrum
• Soft photon spectrum - synchrotron

Rieke & Weekes 1969 – KN (delta-function)

Grindlay & Hoffman 1971
• KN cross section of Jones 1968
• IC spectrum can be used to constrain nebular B field
MHD model of pulsar wind (Kennel & Coroniti 1984)

\[ \sigma \equiv \frac{\text{Magnetic energy density}}{\text{Particle energy density}} = \frac{B_1^2}{4\pi n_1 u_1 \gamma_1 mc^2} \ll 1 \]

(Rees & Gunn 1974)

For the Crab nebula, \[ \sigma \sim 0.003 \]

needed to decrease wind velocity from \( c \) to 2000 km/s
“Second-generation” SSC models

DeJager & Harding 1992 –
- adopted Kennel & Coroniti solution for \( B(r) \) and small \( \sigma \)
- spatial dependence of synchrotron, IC, electrons and photon density

- COS-B sees end of SR spectrum \( \sim 100 \) MeV
- \( E_{\text{max}} = 10^{16} \) eV is near \( V_{\text{open}} \sim 3 \times 10^{16} \) eV acceleration maximum
- Pair multiplicity \( \sim 10^5-10^6 \)
- Upper end of SR spectrum could be variable
“Second-generation” SSC models

Atoyan & Aharonian 1996

- Scattering of CMB and dust contributes \( \sim 10\% \) to IC spectrum
- e-\( \rightarrow \) bremmstrahlung component?
- Two populations of electrons

Meyer et al. 2010

Abdo et al. 2010
MHD simulations

Kalapotharakos et al. 2012

Volpi et al. 2008
Traditional acceleration models

• Diffusive acceleration (1\textsuperscript{st} order Fermi) at termination shock
  (Fermi 1949, Blandford & Ostriker 1978, Eichler 1979)
  – Problem: Crab TS is relativistic and has B nearly perpendicular to flow

\[ V_{\text{shock}} / \Gamma \]

\[ V_{\text{shock}} \]

\[ \rightarrow \text{superluminal} \]

• Resonant absorption of ion-cyclotron waves (Hoshino, Arons, Gallant & Langdon 1992)
  – Problem: requires most of spin-down energy in ions upstream of shock
**Limitations of traditional models**

- No diffusive acceleration at superluminal shocks – not enough turbulence to scatter particles upstream (Sironi & Spitkovsky 2009)

  \[ \dot{\gamma}_{\text{syn}} (\gamma_{\text{max}}) = \dot{\gamma}_{\text{acc}} (\gamma_{\text{max}}) \]

  \[ \gamma_{\text{max}} \propto B^{-1/2} \]

  \[ E_{\text{syn}}^{\text{max}} = \frac{3}{2} \gamma^2 B \approx \frac{9}{4} \frac{mc^2}{\alpha} \approx 160 \text{MeV} \]

- At \( r \sim R_{\text{LC}} \): \( \sigma \sim 10^4 \)

  (PULSAR AND PULSAR WIND THEORIES)

- At \( R_S \): \( \sigma \ll 1(?!?) \)

  (PWN THEORY AND OBSERVATIONS)

Where does energy get transferred from fields to particles??

- Maximum SR energy from acceleration \((E < B)\) limited by synchrotron losses

  (Guilbert et al. 1983, deJager et al. 1996):
Reconnection?

• Reconnection in striped wind (Coroniti 1990)?
  Could solve three problems at once:
  1. Decrease $\sigma$ by transferring energy to particles
  2. enable acceleration at TS
  3. $E > B$ in reconnection layer
     can exceed $E_{\text{syn}}^{\text{max}}$ limit
     (Uzdenzky et al. 2011)

• But reconnection is not fast enough
  - wind $\Gamma$ increases (Lyubarski & Kirk 2001)

• But compression of stripes near shock will drive faster reconnection –
  “shock-driven reconnection”
  (Lyubarski 2003, Lyubarski & Petri 2007)
Shock-driven reconnection

Sironi & Spitkovsky 2011

2D

Particles accelerated at X-points where $E > B$

$\sigma = 10$ $\lambda = 640 \, c / \omega_p$ $\alpha = 0.1$ $\omega_p t = 3750$

$\sigma = 10$ $\lambda = 160 \, c / \omega_p$ $\alpha = 0.1$ $\omega_p t = 990$

3D

Termination shock

Fast MHD shock
Crab flares: reconnection in pair plasma

- Radiation above classical limit in RL
- Flare spectrum from mono-energetic particles with $\gamma \sim 2 \times 10^9$
Crab flares: Doppler boosting

- Flares from variability of Doppler boosting of post-shock flow
  \[ \epsilon_{\gamma}^{\text{obs}} = D\epsilon_{\gamma}, \quad j_{\gamma}^{\text{obs}} = D^{2+\alpha} j_{\gamma} \]
  \[ D = \frac{1}{\gamma(1 - \beta\theta)} \]
- Possibly from inner knot
- Could explain correlation between flux and cutoff energy (Lyutikov et al. 2011)
VERITAS and MAGIC detection of the Crab pulsar

Aliu et al. 2011
Aleksic et al. 2011

- Above 100 GeV, peaks are narrower
- Cutoff of combined spectrum is not exponential (sub-exponential?)
- Extension of Fermi spectrum or separate component (inverse Compton)?
- Is the Crab unique or do other pulsars have > 100 GeV emission as well?
Synchrotron self-Compton emission

Essential ingredients: 1) Energetic particles
2) High synchrotron emission level

Pair cascade spectrum (polar cap)

Energetic pair spectrum and high non-thermal X-rays produce high level of SSC

SSC emission from other young pulsars will be much lower
SSC models of Crab pulsar

- VHE Emission is SSC from pairs
- SSC spectrum reflects pair spectrum
- Possibility of structure in HE spectrum

Preliminary

Slot gap (Harding et al. 2008, Harding 2013)

Annular gap (Du et al. 2012)

Hirotani outer gap
(Hirotsuki et al. 2011)
Summary

• The Crab has been a great playground for theorists
  – IC – no evidence for bremstrahlung or $\pi^0$ emission
  – $\sigma$ problem - solved?
  – High multiplicity problem – time-dependent pair cascades?
  – Acceleration – magnetic reconnection, 1st order Fermi?

• The Crab continues to surprise and challenge us
  – Flaring of gamma-ray synchrotron emission
  – VHE pulsed emission