Pulsar Wind Nebulae observed with ASTROGAM

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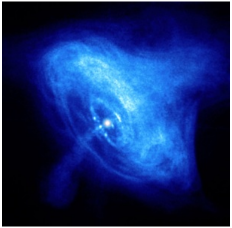
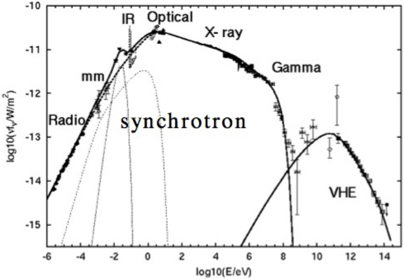
The Crab Nebula and its γ-ray spectrum

- "standard candle" for most of high-energy astronomy



Chandra

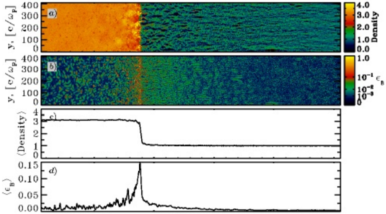


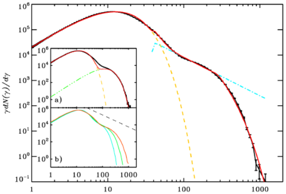
- **synchrotron** emission in most of the electromagnetic spectrum, from $e^{\pm}$ accelerated in the pulsar, wind, termination shock
- TeV γ-ray emission results from **Inverse Compton** scattering of lower-energy photons (synchrotron, CMB, IR, starlight...)

- for most other such *plerions*, non-thermal radiation detected primarily in radio and X-rays, and now often in TeV γ-rays
- PWNe important sources of high-energy cosmic-ray e^{+} (and e^{-})

Fermi acceleration at the relativistic shock?

- Crab Nebula X-ray spectral index $\alpha_X \approx 1.1$ suggests injection of power-law spectrum of electrons with $p \approx 2.2$ (before losses)
- X-ray spectra of most young PWNe have similar α_X values
- consistent with predictions of **relativistic Fermi acceleration** (Kirk et al. 2000, Achterberg et al. 2001, Keshet & Waxman 2005…)
- this requires small-scale turbulence (e.g. Lemoine et al. 2006)
- apparently realised in self-consistent, particle-in-cell (PIC) simulations of **unmagnetised**, $e^{\pm}$ shocks





(Spitkovsky 2008)

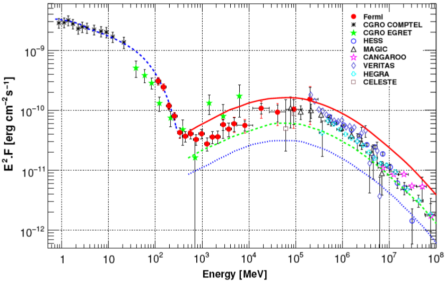
- turbulent fields from Weibel instability (Medvedev & Loeb 1999)
- PWN radio spectra ($\alpha_r \sim 0$) require a different mechanism

Cutoff in Crab synchrotron spectrum

- in this scenario, acceleration time is limited by the downstream gyrotime:

$$t_{\rm acc} \sim \frac{1}{\omega_{\rm c}} = \frac{m_e \gamma c}{e B_{\rm d}}$$

- must be faster than synchrotron losses: $t_{\rm acc} < t_{\rm cool}$
- implies a typical synchrotron cutoff energy $h\nu_{\rm max} \approx 70\,{\rm MeV}$, **independent of B** (de Jager et al. 1996)

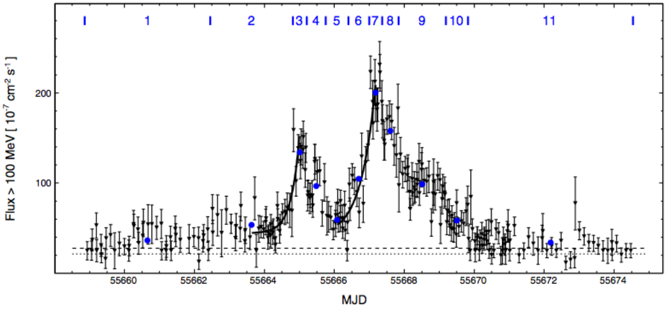


- *Fermi* detects a synchrotron cutoff energy of $(97 \pm 12)\,{\rm MeV}$ (when combined with COMPTEL) (Abdo et al. 2010)

A standard candle flickers: GeV Crab flares!

- dramatic Crab GeV variability ("flares") on day-like time scales found by *AGILE* and *Fermi* (Tavani et al. 2011; Abdo et al. 2011)
- no variation in pulsed spectrum, IC spectrum, other wavelengths
- variability of acceleration near synchrotron cutoff expected, hinted at by *EGRET* (de Jager et al. 1996) (on year time scale)

- intraday rise times in April 2011 flare (e.g. Buehler et al. 2012) :

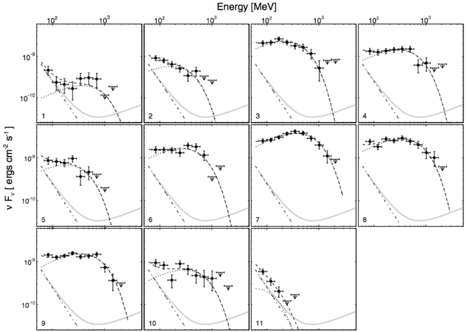


- synchrotron $t_{cool} \sim$ month at cutoff : can't explain these flares

The puzzling Crab Nebula GeV flares (II)

- April 2011 flare shows additional spectral component during flare (above usual synchrotron spectrum, $E_{\gamma,\max} \sim 400\,\mathrm{MeV}$)
- simultaneous variability in few tens of MeV range?

(Buehler et al. 2012)



- also longer-duration (1–2 week) “waves” with intermediate spectral characteristics (Striani et al. 2013)
- do similar phenomena occur in **other Pulsar Wind Nebulae**?

Proposed Crab Nebula flare explanations

Large Doppler boosting factors from bulk motion

- Komissarov & Lyutikov (2011) propose origin in oblique shock responsible for optical knot; Lyutikov et al. (2012) study shock corrugations induced by nebular wave turbulence
- Clausen-Brown & Lyutikov (2012) posit reconnection "mini-jets" with random orientation (and polarisation?)

Short-scale magnetic field fluctuations

- Bykov et al. (2012) propose rapidly fluctuating synchrotron emission from B in **striped wind** shock; predict large pol.
- Teraki & Takahara (2013) propose **jitter radiation**; predict lower polarisation in flares, little TeV-PeV variability

Regions where $E > B$, magnetic reconnection

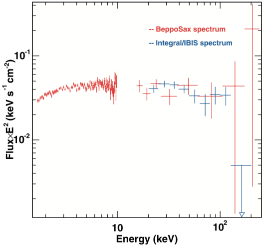
- acceleration with little radiative losses; requires non-ideal MHD
- Uzdensky et al. (2011), Cerruti et al. (2012, 2013) propose acceleration in magnetic reconnection regions in the Nebula

- different model predictions for **polarisation** during flares; ASTROGAM has excellent polarisation capabilities…

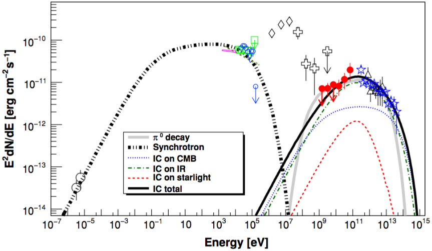
MSH 15–52, the nebula of PSR B1509-58

- *Fermi*-LAT detects only the (TeV-discovered) IC component
- similarly for likely detections of nebulae of PSR J1856+0245 (Roussel et al. 2012) and PSR J1023–5746 (Ackermann et al. 2011)

(Forot et al. 2006)



(Abdo et al. 2010)



- synchrotron spectrum extends with $\Gamma = 2.1$ at least to 100 keV
- INTEGRAL hint of steepening above 100 keV? (Forot et al. 2006)
- no detections in cutoff range, poorly constrained observationally

Expected synchrotron maximum in other PWNe

- acceleration must also be faster than energy losses from adiabatic expansion, $t_{\mathrm{acc}} < t_{\mathrm{exp}}$
- particles must be confined for Fermi acceleration at the shock: $r_{\mathrm{Larmor}} < \varepsilon R_{\mathrm{shock}}$ (with $\varepsilon \sim 0.3$) (de Jager & Djannati-Ataï 2009); this is the more restrictive criterion

- this *geometrical* criterion translates to maximum synchrotron energy:

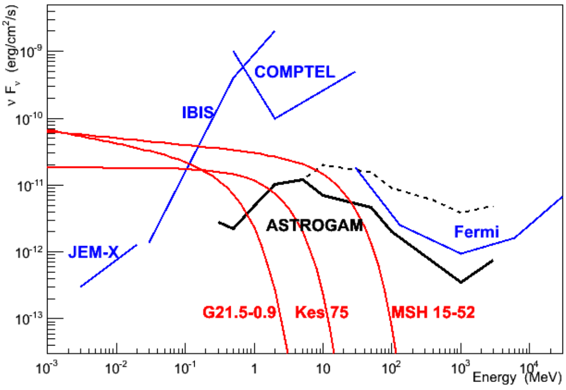
$$h\nu_{\mathrm{max}}^{(\mathrm{geo})} \approx 170\,\mathrm{keV} \times \left(\frac{B_{\mathrm{d}}}{10^{-5}\,\mathrm{G}}\right)^{3} \left(\frac{\varepsilon\, R_{\mathrm{sh}}}{0.1\,\mathrm{pc}}\right)^{2}$$

- this criterion is dominant when $B_{\mathrm{d}} < 75\,\mu\mathrm{G}\,(0.1\,\mathrm{pc}/R_{\mathrm{sh}})^{2/3}$

- PWNe other than Crab: typically $R_{\mathrm{sh}} \leq 0.1$ pc (Bamba et al. 2010)
- as estimated from synchrotron/IC one-zone models, B_{d} = a few tens of microgauss (Torres et al. 2014, and references therein)
- $\Rightarrow$ for most young PWNe, synchrotron cutoff **in MeV domain**

Brightest other PWNe and ASTROGAM

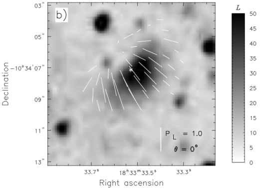
- model PWN spectra based on observed hard X-ray flux, with cutoff as predicted above
- approximate sensitivity curves for existing instruments, ASTROGAM 3-year sensitivity



- ASTROGAM should allow study of $h\nu_{max}$ in several PWNe

Summary : PWN physics with ASTROGAM

- PWNe are laboratories for **relativistic shock acceleration**; ASTROGAM will probe highest accelerated $e^{\pm}$ energies
- **Crab Nebula**: $h\nu_{\rm max}$ limited by synchrotron cooling losses (?)
- **flares**: different mechanisms proposed; ASTROGAM lower-E_γ (< 100 MeV) variability, **polarisation** could help discriminate
- **other PWNe**: $h\nu_{\rm max} \Rightarrow$ constraints on accelerated $e^{\pm}$ transport
- information on post-shock **magnetic field in inner nebula** (most available estimates global, weighted towards outer regions)
- polarisation can constrain magnetic field geometry (e.g. Zajczyk et al. 2012, G 21.5–0.9 observed in near-infrared)
- shed light on "σ problem" (strongly magnetised pulsar wind at magnetosphere $\rightarrow$ weakly magnetised post-shock)



- do other PWNe show **variability** similar to Crab flares?
- maximum accelerated $e^{\pm}$ energy, important for pulsar (wind nebula) contribution to **cosmic-ray positrons** (and electrons)