Possibile interpretazione dei flare nella Crab Nebula

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The Crab Nebula flare observations

- Four intense gamma-ray flaring episodes from the Crab Nebula have been reported in the gamma-ray energy range 100MeV - a few GeV by AGILE and *Fermi*/LAT in the period 2007-2011.

  [M. Tavani et al., *Science* **331**, 736 or 739 (2011); V. Vittorini et al., *ApJ* **732**, L22 (2011)]

- This activity has been attributed to transient emission in the inner Nebula due to the lack of:
  - any variation in the pulsed signal of the Crab pulsar;
  - any detectable alternative counterpart.

- High spatial resolution optical and X-ray observation by Hubble Space Telescope and Chandra detected local enhancement in the "anvil" region.

  [A. Tennant et al., *ATel* **2882**, 1 (2010); P. Caraveo et al., *ATel* **2903**,1 (2010)]

- The emission can be modelled as rapid (within 1day) acceleration followed by synchrotron cooling.

- Assuming a bulk Doppler factor ~ 1 and a local magnetic field $B_{loc} \sim 1$mG, the energy for the synchrotron photons implies that the electrons are accelerated to $\gamma \sim 10^9$.

The striped pulsar wind

- In the equatorial belt, the magnetic field at a fixed radius alternates in direction at the frequency of rotation, being connected to a different magnetic pole every half-period.
- The flow evolves into regions of magnetically-dominated cold plasma, separated by a very narrow, hot, corrugated surface (the current sheet), whose amplitude increases linearly with the distance from the star.
- The wavelength of these oscillations is at most $2\pi r_L$, where $r_L = cP/2\pi$ is the light cylinder radius and P the pulsar period (Crab: $P = 33$ms).
- The current sheet cuts the equatorial plane, and locally it resembles a sequence of concentric, spherical surfaces: *striped wind*.

  [F.C. Michel, *Comments Astro-phys. Space Phys.* **3**, 80 (1971)]
- Only some fraction of the magnetic energy can be converted into particle energy via a magnetic reconnection process in the wind before the termination shock. [Y. Lyubarsky, J.G. Kirk, *ApJ* **547**, 437 (2001)]

- Lyubarsky and Kirk estimated the flow parameters:
  - The maximum distance beyond which the available charge carriers are unable to sustain the current: $r_{max} = \pi \omega_L r_L / 2\Omega$ (where $\omega_L = eB/mc$ is the gyrofrequency at the light cylinder and Ω the pulsar angular velocity);
  - the Lorentz factor of the wind: $\Gamma_w = 0.5 \Gamma_{max} \sqrt{r/r_{max}}$ (where $k \sim 10^3 - 10^4$ is the multiplicity coefficient and $\Gamma_{max} = \omega_L / 2k\Omega$ is the Lorentz factor attained if all the spin-down power is converted into kinetic energy of the plasma);
  - the wind magnetization parameter: $\sigma = \Gamma_{max}/\Gamma_w - 1$;
  - the current sheet width as a fraction of a wavelength $2\pi r_L$ occupied by two current sheets: $\Delta_o \sim \sqrt{r/r_{max}}$.

- In the **Crab Nebula**: $r_{max} \simeq 1.9 \times 10^{19}\mathrm{cm}$, $\Gamma_w \simeq 1.3 \times 10^4 R_{15}^{1/2}$, $\sigma \simeq 2.9 \times 10^2 R_{15}^{-1/2}$, $\Delta_o \simeq 1.1 \times 10^{-3} R_{15}^{1/2}$ (where $R_{15} = r/(10^{15}\mathrm{cm})$)

Shock-driven reconnection and Crab flares

- Lyubarsky analytical model for the particle acceleration via the shock-driven magnetic reconnection: [Y.E. Lyubarsky, *Mon. Not. RAS* **345**, 153 (2003)]
  - Maximal Lorentz factor a particle can attain in the plasma **comoving frame**, when the magnetic field dissipates completely:

$$\gamma_M = \frac{1}{\Delta_o}\left[\frac{2-s}{2(s-1)}\sigma\right]^{1/(2-s)} ;$$

    where $s \sim 1.5$ is the power-law index of particle distribution;
  - maximal energy in the particle distribution in the **laboratory frame**:

$$\gamma_{max} \sim \gamma_M \, \Gamma_w/k \sim \frac{\Gamma_w}{\Delta_o^{s-1}}\left[\frac{2-s}{2(s-1)}\sigma\right]^{1/(2-s)} .$$

- For the **Crab Nebula** $\gamma_{max} \simeq 10^9 R_{15}^{-3/4}$. If a shock forms in a region well inside the termination shock and compresses the pulsar wind at 10^{15}cm from the inner pulsar, this calculation shows that high energy electrons can be accelerated up to $\gamma_{max} \simeq 10^9$ in the laboratory frame.

A collisionless shock compressing the pulsar wind

- We assume that a shell of overdense material of total energy E_o is created in the vicinity of the central pulsar, composed by photon and $e^{\pm}$ pairs, and loaded with baryons: **fireball model**. [T. Piran, *Phys. Rept.* **333**, 529 (2000)]
- Issues against this formulation:
  - Fireball acceleration Γ_f is highly relativistic, at least one order of magnitude larger than Γ_w at 10^{15}cm: the initial shell is *radiation dominated*. Thus, most of the fireball energy content is radiated as thermal emission when the fireball becomes transparent, at $T_{obs} = \Gamma_f \times 20\text{keV} \sim 100\text{MeV}$. It should have been detected by a gamma-ray instrument;
  - in an almost pure radiation fireball, the transparency is reached too early to accelerate the baryons to such a high Lorentz factor;
  - alternative possibility: the fireball is highly magnetized (acceleration driven by magnetic pressure instead of radiation pressure). But the baryon acceleration is even less efficient, scaling as $\Gamma \propto r^{1/3}$.

A plasma instability?

- Required properties of a plasma instability:
  - the shock-induced magnetic reconnection requires necessarily a supersonic compression of particles and of magnetic field characterizing the wind;
  - the wind is strongly dominated by the magnetic energy and the Alfvén velocity is supersonic in the medium.

- We propose the **Weibel instability**: anisotropy of the wind temperature.

  [E.S. Weibel, *Phys. Rev. Lett.* **2**, 83 (1959)]

- Since the compression of the sheet is radial, we can infer a radial propagation of the instability, associated with a different radial temperature of the wind with respect to the orthogonal one.

- Pulsar wind equilibrium distribution function:

$$f_0 = \frac{n}{u_p^2 u (2\pi)^{3/2}} \exp\left[\frac{v_p^2}{2u_p^2} + \frac{v^2}{2u^2}\right] ,$$

where (v_p, u_p) and (v, u) are the particle velocity and its variance on a given plane and in the orthogonal direction, respectively, and n the wind particle density.

- Growth rate for $u_p \gg u$:

$$\gamma(k) = k u_p \omega_p / \sqrt{\omega_p^2 + c^2 k^2} .$$

- At $r \simeq 10^{15}$cm: $n \simeq 10^{-3}\mathrm{cm}^{-3}$, $\omega_p \simeq 10^3 \mathrm{s}^{-1}$. Furthermore, $\omega_p \gg c/\lambda_s$ (where $\lambda_s \gg \lambda_D \simeq 10^7$cm is sheet scale). Thus, on the sheet scale,

$$\gamma \simeq 10\,\mathrm{s}^{-1} .$$

- The Crab wind is collisionless: anisotropy must come from the pair $e^{\pm}$ generation mechanism.