Physics Letters B 739 (2014) 433–438

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The Crab Nebula flaring activity

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ARTICLE INFO

Article history:
Received 6 March 2014
Received in revised form 22 October 2014
Accepted 17 November 2014
Available online 20 November 2014
Editor: S. Dodelson

Keywords:
Gamma rays
Theory – pulsars
Individual
Crab pulsar – radiation mechanisms
Non-thermal

ABSTRACT

The discovery made by AGILE and *Fermi* of a short time scale flaring activity in the gamma-ray energy emission of the Crab Nebula is a puzzling and unexpected feature, challenging particle acceleration theory. In the present work we propose the shock-induced magnetic reconnection as a viable mechanism to explain the Crab flares. We postulate that the emitting region is located at $\sim 10^{15}$ cm from the central pulsar, well inside the termination shock, which is exactly the emitting region size as estimated by the overall duration of the phenomenon ~ 1 day. We find that this location corresponds to the radial distance at which the shock-induced magnetic reconnection process is able to accelerate the electrons up to a Lorentz factor $\sim 10^9$, as required by the spectral fit of the observed Crab flare spectrum. The main merit of the present analysis is to highlight the relation between the observational constraints to the flare emission and the radius at which the reconnection can trigger the required Lorentz factor. We also discuss different scenarios that can induce the reconnection. We conclude that the existence of a plasma instability affecting the wind itself as the Weibel instability is the privileged scenario in our framework.

1. Introduction

The Crab Nebula is one of the most detailed studied astrophysical sources. Its large-scale integrated emission was expected to be steady and it was often used to cross-calibrate X-ray and gamma-ray telescopes and to check their stability over time. The discovery made by AGILE and *Fermi* [1,2] of a short time scale flaring activity in the energy range 100 MeV – a few GeV has represented a really unexpected feature. This emission is thought to be synchrotron emission by the highest energy particles that can be associated directly with an astronomical source, challenging particle acceleration theory.

Attempts to explain the flaring activity of the Crab Nebula have been proposed. Among the most promising there is the possibility to accelerate particles in magnetic reconnection events inside the nebula, and the gamma-ray emission occurs when they enter a region of enhanced magnetic field [3,4]. Alternatively, these reconnection events can occur in "mini-jets" moving relativistically, and the gamma-rays are Doppler boosted toward the observer [5]. The gamma-ray variability may be also related to the changes in the characteristics of the Doppler beaming associated with the structural variability of the termination shock [6,7].

Lyubarsky [8] discussed the possibility that a shock-driven reconnection at the termination shock may transfer energy from the wind magnetic field to the particles, potentially generating an electron distribution with a spectral index ~ 1.5 [see e.g. [9]]. Applying his estimates to the Crab Nebula, he showed that the particles are accelerated to a maximum Lorentz factor, suitable to reproduce the observed radio/optical synchrotron spectrum.

In the present analysis we focus on the overall time duration of the flare (~ 1 day), linking it to emitting region location and to the acceleration mechanism. In particular, we postulate that the emitting region is located at $\sim 10^{15}$ cm from the central pulsar. Then we show that, if similar conditions than the one considered in [8] are fulfilled at $\sim 10^{15}$ cm, hence inside the termination shock, then the electrons can be accelerated up to a Lorentz factor $\sim 10^9$, as required by the spectral fit of the observed Crab flare spectrum. We finally search for a selection criterion among different scenarios that can induce the reconnection. In particular, we discuss an impulsive interaction of the pulsar wind with a shocking material coming out of the pulsar surface or of its magnetosphere, propagating with a supersonic velocity inside the lower dense wind. Then we postulate the existence of a plasma instability affecting the wind itself. We conclude that the second one is the privileged

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http://dx.doi.org/10.1016/j.physletb.2014.11.029

scenario in our framework. The main merit of the present analysis is then to highlight the relation between the observational constraints to the flare emission and the radius at which the reconnection can trigger the required Lorentz factor.

2. The Crab Nebula flare observations

Four intense gamma-ray flaring episodes from the Crab Nebula have been reported in the gamma-ray energy range 100 MeV – a few GeV by AGILE and *Fermi*/LAT in the period 2007–2011 [1,2,10–13]. 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 or of any detectable alternative counterpart [14,15]. No global enhancements are seen in other bands [16–20], but high spatial resolution optical and X-ray observation by Hubble Space Telescope (HST) and Chandra detected local enhancement in the “anvil” region [21,22].

The emission can be modelled [1,10,11] as rapid (within 1 day) acceleration followed by synchrotron cooling: the contribution from inverse Compton emission is negligible. The peak of the gamma-ray spectrum reaches a distinct maximum near 500–800 MeV, well above the constraint for the maximum synchrotron photon energy ~ 150 MeV that can be radiated, assuming equipartition between the electric and the magnetic field [23]. Assuming a bulk Doppler factor ~ 1 and a local magnetic field $B_{loc} \sim 1$ mG (~ 5 times the average magnetic field of the Nebula), this energy for the synchrotron photons implies that the electrons are accelerated to $\gamma \sim 10^9$. This modelling assumes that the acceleration process produces a double power-law differential particle energy distribution, with indices $p_1 = 2.1$ and $p_2 = 2.7$ and break energy $\gamma_{\rm br} = 10^9$: this reproduces the spectrum of the flaring emission and its non-detection at lower energies, except for the enhancement in the anvil region. Finally, the timescale of the flares sets the dimension of the emitting region to be $\sim 10^{15}$ cm.

3. The striped pulsar wind

When the magnetic and rotation axes of the pulsar are not parallel, the time-varying electromagnetic field propagates outwards in the form of electromagnetic waves. 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 in this zone 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 period of the pulsar (for the Crab pulsar $P = 33$ ms). Far from the light cylinder, the distance between successive corrugations is small compared to the radius: the current sheet cuts the equatorial plane, and locally it resembles a sequence of concentric, spherical surfaces. This structure is referred to as a *striped wind* [24].

Lyubarsky [25] showed that, accounting for the pulsar wind acceleration, the distance beyond which the available charge carriers are unable to maintain the necessary current exceeds the radius of the termination shock ($r_{TS} = 3 \times 10^{17}$ cm [26]), so that only some fraction of the magnetic energy can be converted into particle energy via a magnetic reconnection process in the wind before the plasma reaches this shock front, depending on the reconnection rate (see however [27]). A lower limit may be obtained by assuming that the dissipation keeps the width of the current sheet equal to the particle Larmor radius, which is roughly the same condition as the current velocity being equal to the speed of light [28,29,25]. With this assumption, Lyubarsky [25] estimated the parameters of the flow (see also [8]): **a)** the maximum distance beyond which the available charge carriers are unable to sustain the current: $r_{max} = (\pi \omega_L)/(2\varOmega) r_L$, where $\omega_L = eB/mc$ is the gyrofrequency at the light cylinder and $\varOmega$ the pulsar angular velocity; **b)** the Lorentz factor of the wind: $\varGamma_w = 0.5 \varGamma_{max} \sqrt{r/r_{max}}$, where k is the multiplicity coefficient, which is expected to be large ($k \sim 10^3 - 10^4$) and $\varGamma_{max} = (\omega_{)})/(2k\varOmega)$ is the Lorentz factor attained if all the spin-down power is converted into kinetic energy of the plasma; **c)** the wind magnetisation parameter: $\sigma = (\varGamma_{max})/(\varGamma_w) - 1$; **d)** the current sheet width as a fraction of a wavelength $2\pi r_L$ occupied by two current sheets: $\Delta \sim \sqrt{r/r_{max}}$.

In the Crab Nebula we have: $r_{max} \simeq 1.9 \times 10^{19}$ cm, $\varGamma_w \sim 1.3 \times 10^4 R_{15}^{1/2}$, $\sigma \sim 2.9 \times 10^2 R_{15}^{-1/2}$, $\Delta \sim 0.0011 R_{15}^{1/2}$, where $R_{15} = r/(10^{15}$ cm).

4. Acceleration of particles by shock-driven reconnection and the Crab flares

The magnetic reconnection is a direct mechanism to accelerate particles which is naturally able to explain emission frequencies above the synchroton limit, because within the current sheet the magnetic field is almost vanishing and the inductive electric field can efficiently accelerate the electrons (see e.g. [3,4] for an application of this mechanism in the context of the Crab Nebula flares).

In what follows we adopt the analytical model of particle acceleration in a shock-driven reconnection proposed by Lyubarsky [8] that estimates the maximal energy particles can attain when the magnetic field annihilates completely in a pulsar wind as that described in the previous section. The main results of this model have been confirmed by 2D and 3D Particle-In-Cell simulations [9]. Let us consider a region of length $l_\circ$ (in the direction parallel to the equatorial plane) containing two stripes of oppositely directed magnetic field and a current sheet of width[1] δ between them (for a picture of this configuration we refer to Fig. 2 in [8]). Within the current sheet the magnetic field is zero and a resistive electric field is generated, along which the current may flow unbound and particles gain energy from it. If this region is compressed by a shock in a direction orthogonal to the sheet, the reconnection rate is enhanced. The magnetic field dissipates completely when the size of the region transverse to the sheet due to the compression becomes $l_\circ \to l \sim \delta$.

The particle energy distribution within the current sheet in the plasma comoving frame is $N(\gamma) = K\gamma^{-s}$ at $1 \leqslant \gamma \leqslant \gamma_M$. Acceleration of relativistic electrons via magnetic reconnection leads to a power-law particle distribution with index $s \sim 1.5$ [30,31,9,32]. Thus, the particle density is dominated by low-energy electrons, while the energy density is dominated by high-energy electrons. As in [8], we assume that the power-law index s remains fixed in the compression and only γ_M varies, and as a further condition we impose that the sheet width is equal to the maximal gyroradius $\delta = \frac{m_e c^2 \gamma_M}{eB}$. The resulting maximal Lorentz factor a particle can attain in the plasma comoving frame when the magnetic field dissipates completely is:

$$\gamma_M = \frac{1}{\Delta_\circ} \left[\frac{2-s}{2(s-1)} \sigma \right]^{1/(2-s)}, \tag{1}$$

where σ is the initial magnetisation parameter and $\Delta_\circ$ is the current sheet width as a fraction of a wavelength $2\pi r_L$ occupied by two current sheets. The compression factor $k = l_\circ / l$ necessary for

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[1] We assume that, being $r \gg r_{LC}$, the current sheet corrugations can be considered as spherical, concentric current sheets, see Section 3.