The outer gap as the location where charged particles accelerate energy emission from pulsar magnetospheres. They proposed the observations in the gamma-ray band. (IC) upscattering of UV photons into the VHE band can explain 100 GeV and, furthermore, demonstrate that inverse Compton radiation mechanism to explain the observed emission above very difficult to invoke curvature radiation as the dominant the case of the Crab pulsar. In this paper we show that it is us to stringently constrain the VHE emission mechanisms in 2008) and recently at 120 GeV by the VERITAS Collaboration

The recent launch of the Fermi Gamma-Ray Space Telescope and subsequent detection of a large number of pulsars (Abdo et al. 2010b) revolutionized our picture of the non-thermal emission from pulsars in the gamma-ray band from 100 MeV up to about 10 GeV. At even higher energies, in the very high energy (VHE) band, the detection of the Crab pulsar at 25 GeV by the Magic Collaboration (Aliu & MAGIC Collaboration 2008) and recently at 120 GeV by the VERITAS Collaboration (Aliu & VERITAS Collaboration 2011) in the VHE band allow us to stringently constrain the VHE emission mechanisms in the case of the Crab pulsar. In this paper we show that it is very difficult to invoke curvature radiation as the dominant radiation mechanism to explain the observed emission above 100 GeV and, furthermore, demonstrate that inverse Compton (IC) upscattering of UV photons into the VHE band can explain the observations in the gamma-ray band.

Cheng et al. (1986a) were amongst the first to discuss the high-energy emission from pulsar magnetospheres. They proposed the outer gap as the location where charged particles accelerate to relativistic energies and radiate in the gamma-ray band. The outer-gap model is currently one of the most favored models to explain non-thermal radiation from pulsars. Based on the idea of the outer gap, geometrical models are very successful in explaining the basic features of the observed $\gamma$-ray light curves (e.g., Romani & Yadigaroglu 1995; Harding et al. 2008; Bai & Spitkovsky 2010). While there seems to be broad consensus that the particle accelerator is located in the outer magnetosphere, the radiation physics remain controversial. Cheng et al. (1986b, p. 522) discussed the curvature and the IC processes for the Crab and Vela pulsars and concluded that the “Crab primary outer gap $e^+/e^-$ lose most of their energy to curvature $\gamma$-rays.” Curvature radiation has remained the preferred gamma-ray emission mechanism (Romani 1996; see also Cheng et al. 1986a, 2000; Takata et al. 2008; Tang et al. 2008). Possible importance of the IC scattering was discussed in application to the Vela pulsar (e.g., Cheng et al. 1986b; Romani 1996), but was not considered as the primary emission mechanism for the VHE photons.

The purpose of this paper is to argue that in Crab and in a number of other pulsars, IC scattering is the main emission mechanism of the VHE $\gamma$-ray emission. We are trying to give the most general arguments, which are mostly independent of the numerous possible particular details of a full radiative model, leaving the more detailed calculations to a subsequent paper. Overall, we adopt the Cheng et al. (1986b) paradigm of pulsar high-energy emission, but with IC scattering playing a more important role that previously assumed.

This paper is structured in the following way. In Section 2 we demonstrate that the recent results obtained with Fermi (Abdo et al. 2010b), MAGIC (Aliu & MAGIC Collaboration 2008), and especially VERITAS (Aliu & VERITAS Collaboration 2011) make it highly unlikely that curvature emission is the main radiation mechanism of photons above 10 GeV energies from the Crab pulsar. In Section 3 we show that IC scattering by secondary particles in the outer gaps is broadly consistent with the observed luminosity in the VHE band.

2. LIMITS ON CURVATURE RADIATION

2.1. Crab Pulsar

Curvature radiation is a widely discussed process used to explain the observed gamma-ray emission from the magnetosphere of pulsars. In this section we discuss the difficulty of invoking curvature radiation as the emission process that explains the observed pulsed emission from the Crab pulsar above 100 GeV.
We assume an outer-gap scenario with the accelerating electric field being parallel to the magnetic field (Cheng et al. 1986a). In the electric field, a beam of charged particles accelerates—hereafter the primary beam—which has a particle density of the order of the Goldreich–Julian density $n_{GJ}$ (Goldreich & Julian 1969). The primary beam loses a significant amount of its energy through various radiative processes, of which the curvature emission and the IC-induced pair production are the dominant ones (Arons 1983; Cheng & Ruderman 1977). The pair-production process results in the formation of a second population of particles—hereafter the secondary plasma—which has a higher particle density than the primary beam but a smaller bulk Lorentz factor. Within this outer-gap framework we derive a general upper limit on the break in the curvature-radiation spectrum that is emitted by particles within the outer gap of the Crab pulsar. The limit we obtain is independent of the particular details of the acceleration mechanism of the primary beam. In our argument, we follow a similar approach which has been applied before in the discussion of the synchrotron emission from pulsar wind nebulae by de Jager et al. (1996) and Lyutikov (2010).

Within the outer gap, the charged particles follow the curved magnetic field lines and, therefore, emit curvature-radiation photons. The curvature-radiation spectrum emitted by monoenergetic particles has a break at energy $\epsilon_{br}$ (Zheleznyakov 1996)

$$\epsilon_{br} = \frac{3}{2} \frac{\hbar c}{R_c} \gamma_b^3,$$  

where $R_c$ is the curvature radius of the magnetic field lines and $\gamma_b$ is the Lorentz factor of the radiating particles.

An upper limit of $\gamma_b$ is set by the constraint that while the particles accelerate they radiate and, therefore, the maximum value of $\gamma_b$ is obtained when acceleration gains are balanced by radiative losses, i.e., the radiation reaction limit. Under the assumption that the accelerating electric field $E$ is a fraction $\eta \leq 1$ of the magnetic field $B$, the acceleration gain is $e c \eta B$, where $e$ is the electron charge. The radiation reaction limit is then reached if

$$e c \eta B = \frac{2}{3} \frac{e^2}{c} \gamma_b^3 \left( \frac{e}{R_c} \right)^2,$$  

where the losses due to curvature radiation are given on the right side. Using Equation (2) it follows from Equation (1) that

$$\epsilon_{br} = \frac{3}{2} \frac{\hbar c}{R_c} \left( \frac{B}{e} \right)^{3/4}.$$  

(3)

The radius of curvature $R_c$ can be expressed in units of the light cylinder $R_L$, $R_c = \xi R_L = \xi e P/(2\pi)$, where $P$ is the period of the pulsar and $\xi$ is a dimensionless scaling parameter. If, furthermore, $B$ is the radial distribution of the magnetic field of a dipole $B = B_{NS} (R_{NS}/R)^3$, where $B_{NS}$ is the magnetic field on the surface of the neutron star and $R_{NS}$ is the star’s radius, then it follows that

$$\epsilon_{br} = \frac{3}{2} \frac{\hbar c}{R_c} \left( \frac{B_{NS} R_{NS}^3}{e} \right)^{3/4}.$$  

(4)

In the gamma-ray band, a few dozen pulsars have been detected with the Fermi-LAT detector. The spectral energy distributions (SEDs) of these pulsars in the $\gamma$-ray band are very similar and can be characterized by a flat spectral component between 100 MeV and a few GeV (Thompson et al. 1999; Abdo et al. 2010b) and a spectral break in the GeV region. In Figure 1 we compare the observed spectral breaks of these pulsars with the predicted ones from Equation (4) by calculating the ratio of the observed $E_{br}$ and predicted spectral break $\epsilon_{br}$ for each of the 46 pulsars reported in the first Fermi catalog (Abdo et al. 2010b). For the calculation of the break energy $\epsilon_{br}$ we used the extreme case of $\eta = \xi = 1$. If the spectral break is due to curvature radiation and the electric field in the gap is much less than one, $\eta \ll 1$, as it is expected in present outer-gap models, the ratio should be much smaller than one. This is indeed the case for the majority of the pulsars, including the Crab pulsar. However, for a significant number of pulsars, the ratio is close to one and for one pulsar, PSR J1836 + 5925, the ratio is even

$$\frac{0.0}{0.2}/\br = \frac{0.4}{6.0}/\br = \frac{0.6}{8.0}/\br = \frac{1.0}{1.2}/\br = \frac{1.4}{1.6}/\br.$$  

(5)

We note that $\eta$ is a dimensionless scaling parameter. (A color version of this figure is available in the online journal.)

On the very right side we parameterized $\eta = 10^{-2.9} \eta_{-2}$, assuming that the electric field is a few percent of the magnetic field. In the current outer-gap models (Cheng et al. 1986a, 2000; Takata et al. 2008; Tang et al. 2008) an electric field of $E_{\eta} \approx (\Omega B r^2)/(e R_c) \sim 0.1 B$ is predicted, while in the models of Cheng et al. (2000), Takata et al. (2008), and Tang et al. (2008), the accelerating field is one order of magnitude smaller.
larger than one. In order to explain the spectral break for these pulsars as a result of curvature radiation an accelerating electric field is required that is close to or even larger than the magnetic fields.

Two possible interpretations of these results are (1) the observed spectral break is due to curvature radiation by the electrons with the highest energies. For the Crab pulsar a new component dominates above the break and explains the non-exponential cutoff. In this interpretation, the pulsars, for which the ratio $E_{br}/E_{0}$ is close to unity, can be explained by statistical outliers (uncertainties on $E_{br}$ are not taken into account in Figure 1), or that a different emission mechanism dominates at high energies that influences the measurement of $E_{br}$. (2) The gamma-ray emission above ~GeV energies is due to one single emission process, which is not curvature radiation. In this case, the spectral break reflects the underlying particle distribution.

3. IC MODEL OF THE HIGH-ENERGY GAMMA-RAY EMISSION FROM THE CRAB PULSAR

3.1. Outline of the Model

In this section we outline the key features of a synchrotron self-Compton (SSC) model that is able to explain the high-energy emission of the Crab pulsar. Observationally, the SED of the Crab pulsar has a broad peak in the 10–100 keV range with a luminosity $L_{X} \approx 10^{36}$ erg s$^{-1}$ (cf. Figure 9 in Kuiper et al. 2001) which is a few percent of the pulsar’s spin-down power of $\approx 5 \times 10^{38}$ erg s$^{-1}$. Between 10 MeV and the spectral break at a few GeV the SED is flat and has a luminosity $L_{\gamma}$ of a few $\times 10^{34}$ erg s$^{-1}$ (Abdo et al. 2010a). Above the spectral break at $\geq 150$ GeV the luminosity is $\approx 10^{33}$ erg s$^{-1}$.

We identify the broad soft UV–X-ray peak in the SED of the Crab pulsar as a synchrotron (or possibly cyclotron) emission from the secondary plasma boosted by the large parallel velocities of emitting particles. This creates target photons for IC scattering both by the primary beam and by the secondary plasma. As we demonstrate below, the IC scattering by the secondary plasma is broadly consistent with the observations.

3.2. IC Scattering by the Primary Beam

In this section we discuss the IC scattering by the primary beam in the outer gap. We use, like in the previous section, $\epsilon = \eta B = 10^{-2} \eta_{-2} B$ for the accelerating electric field and $\eta_{G} R_{IC}$ with $\eta_{G} = 0.1 \eta_{-1}$ for the effective emitting volume. In order to simplify our calculations, we separate the broad UV–X-ray peak into two components: a low-energy component that covers the UV band with a luminosity of $L_{UV} \approx 10^{34}$ erg s$^{-1} \lambda_{4}$ and typical photon energies of $\epsilon_{soft} = 1$ eV $\epsilon_{UV,0}$ and a high-energy component that is centered around the X-ray peak with a luminosity of $L_{X} \approx 10^{36}$ erg s$^{-1} \lambda_{36}$ and typical photon energies of $\epsilon_{soft} = 1$ keV $\epsilon_{X,3}$. The need to separate the broadband component into two comes from the strong dependence of the IC scattering in the Klein–Nishina (KN) regime on the energy of the photon.

The properties of IC scattering strongly depend on whether the scattering occurs in the Thompson regime or in the KN regime. The regime in which the scattering takes place is determined by the Lorentz factor of the scattering particle and the energy of the upscattered photon (Blumenthal & Gould 1970). For a given photon energy $\epsilon$ the scattering takes place in the KN regime if the Lorentz factor $\gamma_{KN}$ is larger than

$$\gamma_{KN} = \frac{1}{4} \frac{m_{e} c^{2}}{\epsilon_{soft}} \approx 1.2 \times 10^{5} \epsilon_{UV,0}^{-1} \approx 1.2 \times 10^{2} \epsilon_{X,3}^{-1}. \quad (5)$$

These are fairly modest Lorentz factors considering the above estimate of the maximum Lorentz factor that can be achieved in the outer gap in the radiation reaction limit, Equation (4). It can, therefore, be concluded that IC scattering by the primary beam takes place in the KN regime.

Adding losses due to IC scattering in the extreme KN limit into the balanced gain loss Equation (2) results in a net energy loss of (Blumenthal & Gould 1970; Schlickeiser & Ruppel 2010)

$$\dot{\epsilon} = e\epsilon c \eta B - \frac{2}{3} \epsilon^{-2} c \gamma_{4} \left( \frac{c}{K_{e}} \right)^{2} - \frac{4}{3} \left( \frac{m_{e} c^{2}}{\epsilon_{soft}} \right)^{2} U_{soft} \sigma_{T c}, \quad (6)$$

where $U_{soft}$ is the energy density of the target photon field, $\epsilon_{soft}$ is the typical energy of a soft photon, and $\sigma_{T}$ is the Thompson cross-section. Note that both the acceleration term and the decelerating IC term are independent of the energy of the particle. Thus, if curvature losses were negligible, particles are either accelerated or decelerated without reaching a steady solution. Only in the presence of curvature radiation is it possible to achieve a steady-state particle distribution.

In order to better understand how curvature radiation and IC scattering contribute to the radiation loss of the primary beam in Equation (6) we compare the two. In this comparison we assume the curvature-radiation-limited Lorentz factor, Equation (4), and justify our choice post factum by showing that curvature radiation and IC losses in the Crab pulsar are about equal. The soft photon luminosity that results in IC losses in the KN regime which are similar to curvature radiation losses is

$$L_{soft, crit} = \frac{B_{NS} R_{NS}^{2} \epsilon_{UV}^{1/2}}{10^{18} \text{erg s}^{-1} \epsilon_{UV,0}^{-1/2} \eta_{-2}^{-1}} \left[ 10^{35} \text{erg s}^{-1} \epsilon_{UV,0}^{1/2} \eta_{-2}^{-1} \epsilon_{X,3}^{-1/2} \eta_{-2}^{-1} \right]. \quad (7)$$

The minimum luminosity of the target photon field in the UV that is needed to achieve IC losses similar to curvature radiation losses (Equation (7)) is about the same as the observed UV luminosity. The upscattering of soft X-ray photons, even though the X-ray flux is higher than the UV flux, does not contribute much to the radiative loss of the primary beam (KN suppression) because the observed X-ray luminosity is five orders of magnitude below the critical luminosity.

The conclusion that the IC upscattering of UV photons and curvature radiation contribute about equally to the total loss of the primary beam means that both processes also contribute equally to the emitted power in the gamma-ray band. However, the two processes produce very different spectral features. As we have shown before, curvature-radiation photons can only be emitted with energies up to a few GeV for reasonable electric fields and curvature radii; see Equation (4). The spectrum of the IC upscattered photons, on the other hand, extends to much higher energies. This can be shown by assuming again that curvature radiation and IC losses are about equal, in which case the maximum Lorentz factor can still be estimated with Equation (4). The maximum energy of the upscattered photons, $\epsilon_{\gamma}$, is then given by the maximum photon electron energy:

$$\epsilon_{\gamma} \approx \gamma_{0} m_{e} c^{2} = (3\pi)^{1/4} \frac{m_{e} c^{7/4}}{\epsilon_{1/4}^{1/4}} \eta^{1/4} \sqrt{\xi} \frac{B_{NS}^{1/4} R_{NS}^{3/4}}{P^{1/4}} \approx 15 \text{ TeV} \eta_{-2}^{-1/4} \sqrt{\xi}. \quad (8)$$
While the maximum photon energy produced by IC scattering depends on the maximum electron energy, the total power emitted by IC scattering is independent of the electron energy. Instead, the total power is determined by the low-energy target photons field. Due to the steeply falling IC cross-section in the KN regime with increasing energy of the target photons \( \propto \epsilon^{-2} \), the maximum IC power \( L_{\text{KN}} \) might not be determined by the peak luminosity in the SED of the target photons but be at lower energies:

\[
L_{\text{KN},\nu} = \left( \frac{m_e c^2}{\epsilon_{\text{soft}}} \right)^2 U_{\text{soft}} \sigma_T c \times n_{\text{GI}} \times \eta_{GJ} R_{\text{LC}}^3. \tag{9}
\]

Application to the Crab pulsar yields that the primary beam produces an IC luminosity by upscattering the X-ray photons with keV energies and, luminosity of \( L_X \sim 10^{36} \) erg s\(^{-1}\), that is,

\[
L_{\text{KN},X} = 5 \times 10^{29} \eta_{GJ} \epsilon_{x,3}^{-2}. \tag{10}
\]

This is much lower than the IC luminosity produced by upscattering the UV photons with eV energies, \( L_{\text{UV}} \sim 10^{34} \) erg s\(^{-1}\):

\[
L_{\text{KN,UV}} = 5 \times 10^{33} \eta_{GJ} \epsilon_{x,3}^{-2} \epsilon_{\text{UV},0}. \tag{11}
\]

The above is an estimate of the peak power. The average luminosity is lower by at least one order of magnitude. Thus, we conclude that the IC scattering by the primary beam is unlikely to be the origin of the VERITAS signal.

3.3. Gamma-Ray Emission from the Secondary Plasma

In the previous section we discussed the gamma-ray emission produced by the primary beam. In this section we discuss the gamma-ray emission by the particles that are produced in pair cascades of the particles in the primary beam, the secondary plasma.

We recall that the primary beam has a density \( n_{\text{GI}} \) and a Lorentz factor \( \gamma_b \) (Equation (4)). As nomenclature for the secondary plasma we use \( n_p \) for its density and \( \gamma_p \) for its Lorentz factor. We assume energy equipartition between the primary beam and the secondary plasma (the assumption of equipartition between the primary beam and secondary plasma is justified in the polar cap models; Daugherty & Harding 1996; we assume a similar parameterization here). From equipartition it follows that \( n_p \gamma_p = n_{\text{GI}} \gamma_b \). The two particle populations are connected through the pair cascading process, i.e., \( n_p = \lambda_p n_{\text{GI}} \), where \( \lambda = 100\lambda_2 \) is the multiplicity factor of the secondary particles. Multiplicities of the order \( \lambda \sim 10^2 \) are typical in outer-gap models (e.g., Wang & Hirota 2011), but can also reach much higher values, \( \lambda \sim 10^6 \) (Takata et al. 2010).

In our picture of a radiation-reaction-limited acceleration of the primary beam it follows that the Lorentz factor of the secondary plasma is given by

\[
\gamma_p \approx \gamma_b / \lambda = 3 \times 10^5 \eta_{x,2}^{1/4} \sqrt{\xi} \lambda_2^{-1}. \tag{12}
\]

This Lorentz factor is above the minimum \( \gamma_{\text{KN}} \). Therefore, IC scattering by the secondary plasma takes place in the KN regime and we can use the same relations that we have derived in the previous section for the emission produced by the primary beam. (For multiplicities much higher than the assumed \( \lambda \approx 100 \) the scattering by UV photons occurs in the Thompson regime. Overall, the convolution of the electron and the soft photon spectrum requires detailed radiative calculations which include global magnetospheric models and anisotropic angular distributions of the photons.) The maximum energy of IC photons produced by the secondary plasma is (cf. Equation (8))

\[
\epsilon_{\nu,p} \approx \gamma_p m_e c^2 = 150 \text{GeV} \eta_{x,-2}^{1/4} \sqrt{\xi} \lambda_2^{-1} \tag{13}
\]

and the peak luminosity of the IC scattered UV photons is (cf. Equation (11))

\[
L_{\text{KN,p}} = \lambda L_{\text{KN},\nu} = 4 \times 10^{35} \eta_{G,1}^{-1} \epsilon_{\text{UV},0}^{-2} \epsilon_{p,2}. \tag{14}
\]

Both the energy (Equation (13)) and the peak luminosity (Equation (14)) are consistent with the VERITAS detection. Thus, IC upscattering of UV photons by the secondary plasma can explain the observed pulsed emission from the Crab pulsar above 100 GeV. We leave a more detailed calculation of the spectrum to a future paper (we expect that the overall spectrum will depend on the distributions both in parallel \( p_\parallel \) and perpendicular \( p_\perp \) momenta).

The secondary plasma also produces synchrotron photons with energies that can be estimated, e.g., using Doppler-boosted cyclotron emission:

\[
\epsilon_{x,p} = \hbar \omega_B \gamma_p = \eta_{x,4}^{1/4} \sqrt{\xi} \frac{\hbar \omega_B \sqrt{3k eV}}{\lambda m_e c^{13/4}} = 3 \text{keV} \eta_{x,-2}^{1/4} \sqrt{\xi} \lambda_2^{-1}. \tag{15}
\]

This roughly coincides with the energy where the Crab pulsar emits most of its power (in fact, the Crab emits most of its power around 100 keV).

As a check to the above estimates, let us independently estimate the total number of emitting particles (and thus the multiplicity) and their typical parallel and perpendicular momentum. To produce the observed synchrotron luminosity \( L_{\parallel} \approx N_p (e^2 / c) \omega_B^2 \gamma_p^2 \gamma_{\perp} \approx 10^{36} \) erg s\(^{-1}\) at a typical energy \( \epsilon_{\parallel} \approx \hbar \omega_B \gamma_p^2 \Gamma \) \( (N_p \) is the total number of secondary particles in the magnetosphere, \( \gamma_{\perp} \) is a typical transverse Lorentz factor) one requires

\[
N_p \approx \frac{c \bar{L}_{\parallel}}{\gamma_p^2 e \epsilon_{\parallel} \omega_B} = 5 \times 10^{32} \epsilon_{\text{UV,0}}^{-1} \epsilon_{p,2}^{-1/2}. \tag{16}
\]

This demonstrates that for the chosen parameters \( \gamma_{\perp} \sim 1 \), the soft emission occurs in the cyclotron regime, and it also shows that the overdensity

\[
\lambda = \frac{N_p}{n_{\text{GI}} R_{\text{LC}}^3} \approx 70 \gamma_{p,2} \epsilon_{\text{UV,0}}^{-1} \tag{17}
\]

is consistent with our assumption of \( \lambda_2 \sim 1 \).

We, therefore, conclude that emission from the secondary plasma is not only able to explain the observed gamma-ray emission above 100 GeV by upscattering UV photons but it also explains the bulk of the X-ray emission. An obvious modification is required to this simplified picture to include the relativistic momenta of the secondary particles that are transverse to the magnetic field lines and result in synchrotron and not cyclotron emission as we assumed.

4. EXPECTED X-RAY–γ-RAY CORRELATIONS

Within the framework of the SSC model, the power emitted by IC is related to the power of the seed photons. Photons of...
different energies that are emitted by the same particles should
in principle produce similar pulse profiles. In our model, one
expects, therefore, that the pulse profiles in X-ray and in gamma
rays are similar because the secondary plasma emits synchrotron
radiation in X-rays and IC scatters UV photons into the VHE
band. And indeed, the ratio of the amplitudes of the two pulses
in the pulse profile of the Crab pulsar changes consistently in the
X-rays/soft gamma-ray band and in the high-energy gamma-ray
band. In X-rays, the main pulse dominates over the interpulse.
The ratio changes toward higher energies and reverses in the
soft gamma-ray band at about 1 MeV. Similarly, the main pulse
dominates at 100 MeV (see, e.g., also for the pulse profiles at
lower energies; Abdo et al. 2010b) while at 120 GeV the inter-
pulse clearly dominates over the main pulse (Aliu & VERITAS
Collaboration 2011).

In addition, as we have argued that though IC losses may
be energetically dominant (or similar to curvature emission), in
the KN regime they do not lead to an equilibrium distribution
of Lorentz factors. Hence we expect highly non-stationary
magnetospheric plasma flows. This will lead to highly non-
stationary radiative properties. Since within the SSC model the
soft and hard photon fields are related, we might expect some
$\gamma$-ray–X-ray correlation. Though it is the soft UV photons
that are scattered to the GeV energies, and, formally, one expects
UV–GeV correlation, since X-rays and UV form a continuous
spectral distribution, one also expects X-ray–GeV correlation as
well. Thus, we expect a short timescale statistical correlation
between X-ray and $\gamma$-ray photons.

5. DEPENDENCE OF THE $\gamma$-RAY LUMINOSITY
ON THE SPIN-DOWN POWER IN THE
RADIATION-REACTION-LIMITED REGIME

Here we discuss the dependence of the $\gamma$-ray luminosity on
the spin-down power in the radiation-reaction limit. General-
izing Equation (2), the total luminosity radiated by a primary
beam of Goldreich–Julian density $n_{GJ} = B \Omega/(2 \pi c)$ in the
radiation-reaction-limited regime is

$$L_c = e c B n_{GJ} \eta G R_{LC}^3.$$

where $\eta_G R_{LC}^3$ is the volume occupied by the radiating particles.
Replacing $B$ with a dipole field $B_{NS} \times (R_{NS}/R)^3$ at the light
cylinder $R = R_{LC}$, it follows that

$$L_c \approx \eta_G \frac{B_{NS}^2 R_{NS}^6 \Omega^4}{2 \pi c^3}, \approx \eta_G \dot{E}_{SD},$$

where $\dot{E}_{SD} \approx (B_{NS}^2 R_{NS}^6 \Omega^4 / 2 \pi c^3)$ is the pulsar spin-down power.

Thus, in the radiation-reaction-limited regime, the gamma-
ray luminosity is proportional to the spin-down power, $L_c \propto \dot{E}_{SD}$. This differs from the commonly used $L_c \propto \sqrt{\dot{E}_{SD}}$ scaling,
which results if the maximum particle energy is not limited by
radiation reaction but by the electric potential and most of
the energy is radiated away once the particle is outside of
the accelerating region. This is the case in polar cap models.
In these models a beam with a particle density equal to the
Goldreich–Julian density loses energy $N \propto \eta_{GJ} r_{PC}^2 \propto \sqrt{\dot{E}_{SD}}$
(see, e.g., Zhang & Harding 2000), where $r_{PC}$ is the radius of
the polar cap. The same square-root scaling has been extended
to outer gaps, assuming that the emitting volume is propor-
tional to the volume within the light cylinder radius (Hirotani et al.
2003).

The expected linear proportionality (Equation (19)) of the
$\gamma$-ray luminosity is valid in the radiation reaction limit, i.e., if
the dominant radiation processes depend on the particle energy.
This is the case, for example, for curvature radiation or IC
scattering in the Thompson regime. And it is not the case
for IC scattering in the KN regime, where the radiative losses
are independent of the particle energy (see Equation (5)), and,
therefore, the acceleration is not limited by radiation losses.
However, as we argued in Section 3, there are good reasons to
believe that particle acceleration is indeed limited by radiation
reaction.

We note that testing our prediction is complicated by the
large uncertainty of the geometrical parameter $\eta_G$, the effective
emission volume, which depends on the pulsar inclination angle,
the angle between the rotation axis, and the line of sight. It may
depend on the period of the pulsar through the microphysics of the acceleration. The forthcoming second Fermi
pulsar catalog is expected to shed more light on the true $L_{\gamma} = \dot{E}_{SD}$
dependence.

6. DISCUSSION

The recent detection of the Crab pulsar above 100 GeV by
VERITAS (Aliu & VERITAS Collaboration 2011) changes our
picture of high-energy gamma-ray emission from pulsars. Even
though the breaks in the energy spectra of most pulsars are con-
istent with curvature radiation in the radiation reaction limit.
For some pulsars, exceptional conditions on the accelerating
electric fields are required to explain the observed cutoff energies
with curvature radiation. In particular, the VHE pulsed
emission from the Crab pulsar above 100 GeV can only originate
from curvature radiation if extreme assumptions are being made
about the pulsar’s magnetosphere. The observation that the flux above 100 GeV is in agreement with an extrapolation of the flux from the GeV regime argues in favor of one emission mecha-
nism being dominant below and above the spectral break.

Thus, there are two somewhat independent arguments against
curvature radiation as the dominant source of GeV photons:
(1) in many pulsars the observed break energy is too high;
(2) the Crab pulsar energy spectrum above the break is in-
consistent with what is expected if the break is due to curvature
radiation from particles in the radiation reaction-limited regime.

More precise measurements of the energy spectra of all $\gamma$-ray
pulsars, but especially for those with low break energies, may
be decisive for further progress: For those pulsars for which the
break energy is consistent with curvature radiation and moderate
electric fields, it is then expected that the energy spectrum above
the break follows an exponential cutoff. If, however, the energy
spectra above the breaks are better described by power laws like
those for the Crab, it argues against curvature radiation.

In this paper, we demonstrated that IC scattering in the KN
regime by the secondary particles results in an overall consistent
picture with observations. The key features of our model are
as follows. (1) A population of primaries is accelerated in a
modest electric field, which is a fraction $\eta$ of the magnetic
field strength near the light cylinder with a typical value of
$\eta$ of $10^{-2}$. The suppression of the scattering cross-section
in the KN regime (and the corresponding lower radiation loss
rate of electrons) allows primary leptons to be accelerated to
VHEs with hard spectra. (2) The gain in energy of the primaries
in the electric field is balanced by similar curvature radiation
and IC losses (radiation reaction limited). (3) The secondary
plasma is less energetic, but denser and has approximately
the same energy content as the primary beam. The secondary
plasma is responsible for the soft UV–X-ray emission via synchrotron/cyclotron emission and the high-energy γ-ray emission that extends to hundreds of GeV via the IC process. The IC emission from the primary beam extends well into the TeV regime but will be difficult to detected due to the low predicted fluxes.

Finally, we argued that in the radiation reaction-limited regime the γ-ray luminosity of pulsars should scale linearly with the spin-down energy, Equation (19). The coefficients of this proportionality both depend on the overall geometry of the magnetosphere (e.g., inclination angle of the magnetic dipole with respect to the axis) through the parameters $\eta_{IC}$ and on the electric field in the gap through the parameter $\eta$ (which, in turn, depends on microphysics of the acceleration precesses).

This prediction is in contrast to the currently assumed scaling of the γ-ray luminosity with the available potential, $\propto \sqrt{E_{SD}}$. Observationally, when compared with the scaling of $\propto \sqrt{E_{SD}}$, all models underpredict the luminosity of pulsars and thus fail to describe the observed population (e.g., Pierbattista et al. 2010; for alternative interpretation of the data, see Watters & Romani 2011). The proposed linear scaling of the γ-ray luminosity with the spin-down energy naturally predicts more energetic pulsars.

Here we outlined a framework to explain the non-thermal radiation from gaps in the magnetosphere of pulsars. More detailed calculations of the emitted energy spectra are needed. A major complication in including the IC losses in the radiation codes results from the fact that in the KN regime, an accelerating electric field of a given strength does not lead to a fixed energy of a particle. This means that a particle is either accelerated or decelerated depending on the photon density and the value of the electric field, and does not reach a steady energy. This implies that in this regime acceleration is highly non-stationary. The addition of curvature radiation can, however, establish a steady state. Thus, curvature radiation, even if not dominating the total gamma-ray luminosity, may dictate the particle’s final energy.

A number of additional factors must be taken into account to construct a comprehensive model of the higher energy emission. Most important is the intrinsically non-isotropic distribution of soft photons. A more detailed structure of the magnetic field lines within the magnetosphere needs to be taken into account, including modifications due to magnetospheric currents. Also, particle trajectories may not exactly follow the magnetic field lines due to various drift effects. An important modification could be the IC scattering of the surface thermal emission closer to the surface of the neutron star in the slot gaps (Arons 1983; in comparison, Crab does not show any thermal component; Weisskopf et al. 2004).

The present work excludes curvature emission as the main γ-ray emission mechanism in the Crab pulsar. The case for dominance of IC scattering in the Crab pulsar was, partially, expected due to high soft photon luminosity (e.g., Hirotani 2007). The current model is not sufficiently developed to make inferences about the relative importance of curvature and IC emission in the pulsar population in general, especially considering the fact that so far all radiative models use a stationary approach, which is likely not to be applicable.

Observationally, a strong support for the model will come from the detection of the non-exponential cutoffs in pulsar spectra. In the IC model the spectral peak corresponds to the break in the particle distribution function, which is likely to be of the power law type both below and above the break. Non-exponential breaks can be detected either in the brightest γ-ray pulsar (e.g., Vela and Geminga) or statistically, by stacking pulsar spectra normalized to the break energy.

Our model is based on the assumption that emission is generated within the light cylinder. The main argument for this is that Fermi pulsar profiles are well fitted with geometric models and that the profile of the VHE emission is correlated with the lower energies. This disfavors the models that advocate the emission from the wind zone (e.g., Bogovalov & Aharonian 2000; Kirk et al. 2002).

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