Rotationally driven VHE emission from the Vela pulsar

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ABSTRACT

Context. The recent detection of pulsed $\gamma$-ray emission from the Vela pulsar in the $\sim 10$ to 100 GeV range by H.E.S.S. promises important potential to probe into the very high energy (VHE) radiation mechanisms of pulsars.

Aims. A combined analysis of H.E.S.S. and Fermi-LAT data suggests that the leading wing of the P2 peak shows a new, hard gamma-ray component (with photon index as hard as $\Gamma \sim 3.5$), setting in above 50 GeV and extending beyond 100 GeV. We study these findings in the context of rotationally driven (centrifugal) particle acceleration.

Methods. We analyze achievable particle energies in the magnetosphere of the Vela pulsar and calculate the resultant emission properties.

Results. Inverse Compton up-scattering of thermal photons from the surface of the star is shown to lead a pulsed VHE contribution reaching into the TeV regime with spectral characteristics compatible with current findings. If confirmed by further observations this could be the second case where rotationally driven processes turn out to be important to understand the VHE emission in young pulsars.

Key words. pulsars: individual: Vela pulsar – radiation mechanisms: non-thermal – gamma rays: general – acceleration of particles

1. Introduction

One of the most enigmatic high-energy astrophysical objects is the Vela pulsar (PSR B0833−45). Located at a distance of $d_l \approx 300$ pc (Caraveo et al. 2001) the Vela pulsar is a young pulsar with a period of rotation of $P = 89$ ms, an estimated age of $t = P/(2P) = 1.1 \times 10^5$ yr (Reichley et al. 1970), and a spin-down luminosity of the order of $E = 10^{37}$ erg s$^{-1}$ (Manchester et al. 2005; Mignani et al. 2017).

Pulsed gamma-ray emission from the MeV to GeV domain has been reported by a variety of instruments early on, from SAS-2 and COS B to CGRO, AGILE, and Fermi-LAT (Thompson et al. 1975, 1977; Kanbach 1980; Kanbach et al. 1994; Pellizzoni 2009; Abdol et al. 2009). At high $\gamma$-ray energies its light curve is found to exhibit two prominent peaks, P1 and P2, which are separated in phase by 0.43 and connected by a so-called P3 bridge.

In particular, while Fermi-LAT initially detected high-energy (HE; $\gtrsim 10$ GeV) emission from the Vela pulsar up to $\sim 10$ GeV, further observations have increased this to 20 GeV (Abdo et al. 2010) and 50 GeV (Leung et al. 2014), respectively. At very high energies (VHE; $\gtrsim 100$ GeV) on the other hand, the Vela pulsar has not been seen in early H.E.S.S. observations with an energy threshold of 170 GeV, imposing constraints on a possible inverse Compton (IC) contribution from outer gap models (Aharonian et al. 2007). New results based on H.E.S.S. II (CT5-only) observations in the sub-20 GeV to 100 GeV range have recently been reported (Abdalla et al. 2018), with pulsed $\gamma$-rays from the strong P2 peak (phase interval 0.5−0.6) detected at a significance level of 15$\sigma$. The results for P2 confirm the sub-exponential cutoff shape found at lower energies with Fermi-LAT and support the presence of emission above 100 GeV. Perhaps most intriguingly, there are converging indications for the emergence of a hard spectral component above 50 GeV in the leading wing of the second peak, LW2 (phase interval 0.45−0.5), which possibly extends beyond 100 GeV. A simple power law fit of the H.E.S.S. II data for LW2 with two different energy thresholds, CI and CII, yields comparable photon indices of $\Gamma = 3.72 \pm 0.51$ (CI) and $\Gamma = 3.48 \pm 0.21$ (CII), respectively (Abdalla et al. 2018). Here CI and CII refer to different analysis cuts optimized so as to yield a large effective area in the 10−20 GeV range, with the threshold for CI approaching 5−10 GeV depending on zenith angles, and the threshold being approximately two times higher for CII. If the inferred hardening were to be confirmed by further observations it would point to the presence of a second and new emission component.

Motivated by these indications we study the possible generation of high- and very-high-energy gamma-rays in the context of magneto-centrifugal acceleration (e.g., Machabeli & Rogava 1994; Gangadhara 1996; Osmanov & Rieger 2009, 2017; Bogovalov 2014). As the magnetic field in the magnetospheres of pulsars is extremely high, charged particles will quickly transit to the ground Landau level and start sliding along the magnetic field lines. Since the field is co-rotating with the star, the particle dynamics is likely to be highly influenced by the effects of centrifugal acceleration. This particularly applies for particles approaching the light cylinder (LC) surface.

The possible relevance of this for the origin of the emission in the Crab pulsar was studied early on by Gold (1969), who suggested that this could facilitate an efficient energy transport from the magnetosphere to the pulsar. This idea has been further developed in several studies (e.g., Bogovalov & Sagdeev 1999; Machabeli & Nagodav 2000; Bogovalov et al. 2010). In this approach, the emitted particles experience a non-LTE (non-local thermodynamic equilibrium) ionization and excitation, leading to a high-energy cutoff of the spectrum. This in turn can lead to a significant acceleration of particles, particularly in the outer gaps of the magnetosphere, where the magnetic field is weaker. The resulting gamma-rays could then be detected by current and future gamma-ray telescopes.

This contribution introduces a new mechanism, where rotationally driven processes could play a role in the VHE emission from the Vela pulsar, similar to what has been suggested for the Crab pulsar (e.g., Fichtel et al. 1996; Aharonian et al. 2008). In the following section, we present a simple model to calculate the achievable particle energies in the magnetosphere of the Vela pulsar and the resultant emission properties.
transfer from the rotator into the kinetic energy of plasma particles. Using an idealized model for centrifugal acceleration, Machabeli & Rogava (1994) later showed that incorporation of (special) relativistic effects can lead to a radial deceleration of the particle motion, resembling features known from general relativity (Abramowicz & Prasanna 1990).

As a convenient analog, centrifugal particle acceleration has since been studied in a variety of contexts, for example for predicting the location, for frequency mapping in pulsars (Gangadhara & Lesch 1997; Rieger & Mannheim 2000; Xu 2002; Osmanov et al. 2007, 2014; Ghisellini et al. 2009). In particular, by applying magneto-centrifugal acceleration to Crab-like pulsars it was found that on approaching the LC area, electrons could achieve Lorentz factors up to $\gamma \approx 10^7$ (Osmanov & Rieger 2009; Bogovalov 2014), suggesting that IC scattering in the magneto-sphere of the Crab Pulsar could generate detectable pulsed VHE emission.

This timescale is a continuously decreasing function of $\gamma$, and since the latter formally tends to infinity on the LC, $t_{\text{acc}}$ tends to zero, indicating an extremely efficient process.

It is clear that acceleration cannot be a continuous process and must be terminated. As already mentioned, centrifugal acceleration is provided by the frozen-in condition of magneto-photospheric plasma particles. This condition will only last until the plasma energy density, $n_{\text{pl}}(r)\gamma m c^2$, becomes comparable to the energy density in the magnetic field $B^2/8\pi$, where $n_{\text{pl}}(r) = \omega \cdot B M(2\pi c) = M n_{\text{GJ}}$, which is the Goldreich-Julian particle number density (Goldreich & Julian 1969), taking account of the multiplicity factor, $M = (1 - r^2/r_c^2)^{-1}$. Assuming a dipolar magnetic field structure, $B(r) = B_c \times (r/r_c)^3$, with $r_c = 11.5$ km (e.g., Li et al. 2016), the co-rotation condition imposes a constraint on the maximum attainable electron Lorentz factor of

$$\gamma_{\text{cor}} \approx 6.4 \times 10^6 \left(\frac{\gamma_0}{10^2}\right)^{1/2} \left(\frac{\sin^2 \theta}{\cos \theta}\right)^{1/2},$$

(4)

taking Lorentz factors $\gamma_0 \approx 10^4$ for the secondaries (Daugherty 1982) as reference value. Similar to the emission model proposed by Gold (1969) electrons close to the LC area co-rotate with almost $R_c$, suggesting that curvature $\gamma$-ray emission might be of significance. The corresponding curvature photon energy $3hc\gamma^3/(4\pi R_c)$ is in the range

$$\epsilon_{\text{cur}} \approx 8.7 \times \left(\frac{5 \times 10^6}{\gamma}\right)^{1/3} \text{MeV}.$$  

(5)

Curvature emission could therefore in principle lead to a pulsed $\gamma$-ray contribution in the COMPTEL (1–10) MeV regime. It is clear that curvature emission also introduces some constraints on the maximum attainable energies. The cooling timescale due to curvature emission, $t_{\text{cur}} = \gamma m c^2/F_{\text{cur}}$, where $F_{\text{cur}} = 2c^3\gamma^3/(3R_c^3)$ is the single particle power (Ochelkov & Usov 1980), becomes

$$t_{\text{cur}} \approx 0.25 \times \left(\frac{5 \times 10^6}{\gamma}\right)^3 \text{s}.$$  

(6)

Acceleration would therefore formally be balanced by curvature cooling at

$$\gamma_{\text{cur}} \approx 7.2 \times 10^7 \left(\frac{10^{11} }{\gamma_0}\right)^{1/5} \left(\frac{\sin^2 \theta}{\gamma_0}\right)^{3/5},$$

(7)

assuming $r_0 \ll R_c$. Hence the co-rotation limit (see Eq. (4)) is generally expected to impose the most stringent constraints; see also Fig. 1 for illustration.

The above analysis suggests that rotationally driven curvature emission could lead to a non-negligible $\gamma$-ray contribution at $\sim(1–10)$ MeV energies that could help to alleviate tensions in for example outer-gap spectral energy distribution (SED) modeling of the Vela pulsar (e.g., Takata et al. 2004). One can roughly estimate the possible curvature megaelectronvolt contribution from $F_{\text{cur}} \approx 2n_{\text{GJ}}M \Delta V F_{\text{cur}}$ (see also Eqs. (10) and (11)), yielding $t_{\text{cur}} \sim 10^{-3} (B/6 \times 10^8 G)(\gamma/4 \times 10^4)\epsilon^2/\chi\cos \theta \text{erg}^{-1}$ s. In the COMPTEL regime the flux is of the order of $F_{\text{COMP}} \sim 10^{-10} \text{erg s}^{-1} \text{cm}^{-2}$ (Bennett 1993), translating into an isotropic-equivalent luminosity $L \approx 4\pi d_k^2 F_{\text{COMP}} \approx 10^{33} \text{erg s}^{-1}$. If one assumes that focusing in this energy band is of the same order as in the teraelectronvolt regime, 0.25 sr (see the estimates below), the inferred luminosity $L \sim L_{\text{i}}(0.25/4\pi) \sim 10^{31} \text{erg s}^{-1}$ would be very close to $L_{\text{cur}}$ derived above.
On the other hand, as shown below, rotationally driven IC scattering of thermal soft photons from the surface of the neutron star can lead to a VHE contribution in the $\sim$(0.1–1) TeV regime. This is different from typical outer gap models, which would predict a rising IC contribution peaking at $\sim$10 TeV (e.g., Aharonian & Bogovalov 2003; Takata et al. 2006).

The surface temperature of the Vela pulsar is below the standard cooling curve and probably in the range $T \approx (6–8) \times 10^5$ K (Page et al. 1996; Mori et al. 2004; Weiskopf et al. 2011). We take $T \approx 7 \times 10^5$ K as a reference value in the following. The thermal photons thus have characteristic peak energies of the order of $\epsilon_{th} \approx 2.8kT \approx 0.2$ keV, where $k$ is the Boltzmann constant. If these photons encounter centrifugally accelerated electrons, the former will inevitably gain energy. Since the ratio $\gamma \epsilon_{th}/(mc^2)$ exceeds unity for electron Lorentz factors exceeding $\gamma \approx 2.3 \times 10^5$, IC up-scattering to the VHE regime essentially occurs in the Klein-Nishina (KN) regime where the corresponding single-particle IC power can be suitably approximated by (e.g., Blumenthal & Gould 1970)

$$P_{\text{IC,KN}} \approx \frac{\sigma_T (mc^2)^2}{16\hbar^3} \left( \ln \frac{4yK}{mc^2} - 1.981 \right) \left( \frac{e}{\hbar} \right)^2, \quad (8)$$

with $\sigma_T$ being the Thomson cross section and $h$ the Planck constant. We use the general expression for the electron-loss rate derived in Aharonian & Atoyan (1981) to evaluate the corresponding IC cooling timescale $t_{\text{IC}} = \gamma mc^2/P_{\text{IC}}$. The result is shown in Fig. 1 together with the timescales for curvature losses $t_{\text{curv}}$ and particle acceleration $t_{\text{acc}}$.

As evident from this figure, IC scattering does not impose any constraints on the maximum attainable energies of electrons, the latter essentially being determined by the co-rotation limit.

Despite the negligible role of IC in limiting maximum attainable energies, up-scattering of thermal photons could lead to detectable $\gamma$-ray emission in the VHE energy regime (cf. Bogovalov & Kotov 1992). Scattered (KN) photon energies, $\epsilon_\gamma \approx \gamma mc^2 \sim 100 \left( \frac{\gamma}{2 \times 10^3} \right)$ GeV, (9) may in principle extend into the teraelectronvolt regime (for $\gamma \leq \gamma_{\text{cor}}$), though expected teraelectronvolt flux levels could be too low to allow for a significant detection. The latest H.E.S.S. observations of the Vela pulsar in fact provide indications for $\gamma$-ray emission above 100 GeV (Abdalla et al. 2018). For an order-of-magnitude estimate of the intrinsic rotationally driven IC-VHE (100 GeV) luminosity we take into account the fact that the process of efficient acceleration and radiation production occurs in a thin shell close to the LC (Osmanov & Rieger 2009) whose characteristic width is given by

$$d \approx \left[ \frac{\gamma}{\gamma_{\text{cor}}} \right] \approx \frac{R_{\text{LC}}}{\gamma}, \quad (10)$$

Multiplying the corresponding particle number with the single IC power $P_{\text{IC,KN}}$, Eq. (8), one obtains

$$L_{\text{IC}} \approx 2 n_{\text{0,IG}} M \Delta V P_{\text{IC,KN}} \sim 2 \times 10^{39} \left( \frac{B}{6 \times 10^4 G} \right) \xi^2 \chi \cos \alpha \sin^2 \alpha \text{erg s}^{-1},$$

using $M \sim \gamma_{\text{cor}}/\gamma_0$ and $\gamma_{\text{cor}}/\gamma = 30$, and using $\Delta V = \chi (d\ell)^2 d\ell$ to denote the corresponding volume; $\chi \leq 1$ is a dimensionless factor depending on the topology of magnetic field lines, $d\ell \sim R_{\text{LC}}$, $\theta$ is the azimuthal length involved in this process, and $\theta \sim \Omega P (\xi/10) = 2\pi (\xi/10)$ is the corresponding angle, where $(\xi/10)P$ is an approximate value for the pulse duration ($\xi \leq 10$). Obviously, $L_{\text{IC}} \ll \epsilon$ the spin-down luminosity $\epsilon$.

A rough estimate for the corresponding power in electrons, $E_e$, can be obtained from $E_e = N_e(\gamma) \gamma mc^2e^2$. Here, $N_e$ is the total rate of IC emitting electrons, $N_{\text{IC}} \propto N_0/\gamma_{\text{cor}}^{1/2}$ (cf. Eq. (12)), and $N_0 = n_{\text{0,IG}} M dA \ell$ where $dA \ell = \chi R_{\text{IC}}^2 (2\pi/\theta_{\text{IC}})^2$ using the notation above. Assuming $M \approx \gamma_{\text{cor}}/\gamma_0$ one finds $E_e \sim 10^{32}$ erg s$^{-1}$, again much below the spin-down luminosity $\epsilon \sim 10^{36}$ erg s$^{-1}$ of the Vela pulsar. In principle, polar cap heating by secondary particles flowing back to the neutron star could lead to some excess thermal emission and thereby modify the IC emission. As shown by Harding & Muslimov (2001) however, this effects is expected to be negligible for Vela-type pulsars.

The recent H.E.S.S. analysis suggests isotropic-equivalent VHE (100 GeV) flux levels of the order of $L_e \sim 10^{31}$ erg s$^{-1}$. This would indicate that the VHE emission of the Vela pulsar is collimated with corresponding emission cones confined to solid-angle regions of $\Delta \Omega \approx 4\pi (L_e/(1L_\text{V})) \lesssim 0.25$ sr.

The indications for the emergence of a hard spectral component above 50 GeV in LW2 are particularly interesting, alluding to the possibility that VHE emission well beyond 100 GeV may be present in the Vela pulsar. To investigate the spectral characteristics of rotationally driven VHE in more detail, we follow the description developed in Rieger & Aharonian (2008). Accordingly, assuming electrons are injected at a constant rate, $Q$, into the density distribution along the magnetic field lines can be written as

$$n_e(\gamma) \sim \frac{Q \varepsilon_{\text{acc}}}{\gamma} H(\gamma - \gamma_0) \propto \gamma^{-3/2}, \quad (12)$$

where the behavior $\varepsilon_{\text{acc}} \propto \gamma^{-1/2}$ (see Eq. (3)) has been used. The (effective) differential number of electrons, $N_e(\gamma) = \frac{dN_e}{d\gamma}$, then becomes (Osmanov & Rieger 2017)

$$N_e(\gamma) = n_e(\gamma) \Delta \varepsilon \propto n_e(\gamma) d\varepsilon \propto \gamma^{-5/2}, \quad (13)$$

taking into account that higher-energy particles accumulate in a narrower region close to the LC, with width scaling as $d \propto \Delta \varepsilon.
1/γ. Eq. (10). Inverse Compton up-scattering of thermal soft photons in the KN regime then produces a photon spectrum (Blumenthal & Gould 1970)

\[
\frac{dN_{\gamma}}{d\Omega d\nu} \propto \epsilon_{c,\nu}^{-3.5} \left( \frac{\ln \epsilon \sigma T_k m_e^2 \gamma}{m^2 c^4} - 1.4 \right) - \epsilon_{c,\nu}^{-3.5},
\]

(14)

with a VHE photon index compatible with the ones inferred for LW2, that is, \(\Gamma = 3.72 \pm 0.51\) (CI) and \(\Gamma = 3.48 \pm 0.21\) (CI).

Figure 2 shows the γ-ray SED for the Vela pulsar along with a characteristic model calculation of the expected IC γ-ray contribution using NAIMA (Zabalza 2015). The calculations assume (quasi-isotropic) up-scattering of thermal photons (\(T = 7 \times 10^5\) K) close to LC by an exponential cut-off power-law electron distribution, \(n(\gamma) \propto \gamma^{-\delta} \exp(-\gamma/\gamma_c)\), with \(\gamma_c = 6 \times 10^6\) and \(\gamma_0 = 10^4\). The Fermi-LAT data for P2 and LW2 are illustrated by their best-fit (exponential cutoff power-law model) representations (green and red curve, respectively), as detailed in Abdalla et al. (2018).

In a similar way to in other LC models (e.g., Cheng et al. 1986; Bogovalov & Kotov 1992) we assume that particles leaving the acceleration zone no longer make a significant contribution to the pulsed VHE emission. This could be related to electrons quickly cooling out of the VHE window due to increased synchrotron-curvature losses in bent fields, along with a reduced focusing of the resultant emissions. In particular, particle escaping from the acceleration zone and experiencing non-zero pitch angles (e.g., due to excitation of instabilities close to LC; Machabeli & Osmanov 2010) would immediately cool down on characteristic length scales \(\sim c_{\text{cool}} \propto \gamma \sin \phi \ll R_{\text{lc}}\gamma_0/\gamma_{\text{cut}}\) for a wide range of angles. In the present model one can roughly estimate the possible synchrotron contribution below a few giga-electronvolts via \(L_{\gamma,\text{SC}}(\gamma) \propto N_{\text{syn}} \sim 2 N \left[ \gamma^2 \sigma_{\gamma \gamma}(B^2/8\pi) \sin^2 \theta \right]\), where \(N \sim N_{\text{IC,cool}}\) yielding \(L_{\gamma,\text{SC}} \sim 10^{-2}\) erg s\(^{-1}\). On the other hand, for a more detailed spectral modeling, quasi-linear diffusion and the maintenance of pitch angles would have to be incorporated (Machabeli & Osmanov 2010); this is however beyond the scope of the current paper.

As can be seen in Fig. 2, rotationally driven IC γ-ray emission may reach into the teraelectronvolt regime, but become apparent below \(\sim 100\) GeV only for LW2. These results motivate detailed VHE studies with higher sensitivity, as well become possible with CTA South (Burtovoi et al. 2017), in order to better characterize the γ-ray emission above \(\sim 100\) GeV. If confirmed by further observations, this would highlight the relevance of incorporating rotationally driven effects for our understanding of the γ-ray emission in young pulsars.

Taking account of the angular dependency in Eq. (4) suggests that rotationally driven IC emission could well yield VHE emission up to several teraelectronvolts. When compared to the Crab pulsar, where rotationally driven curvature emission can lead to a detectable gigaelectronvolt contribution (Osmanov & Rieger 2017), supporting a smoother GeV-VHE connection, as indeed seen (Ansoldi et al. 2016), rotationally driven curvature emission in the Vela pulsar peaks at megarelectronvolt energies only (Eq. (5)); rotationally driven IC VHE component in the Vela pulsar thus appears as a separate, second and new component.

We note that rotational acceleration in principle predicts a decrease in individual pulse width with increasing energy. Neglecting local changes in the field topology, the observed pulse duration is roughly proportional to \(\gamma_0^3\) (Rybicki & Lightman 2007), where \(\gamma_0 = \left(1 - \epsilon_0^2/c^2\right)^{-1/2}\) is the azimuthal Lorentz factor. Taking into account Eq. (2) we approximately have \(\gamma_0 \sim (\gamma/\gamma_0)^{1/2}\). Hence, for VHE emission with γ \(\sim 10^6\) and \(\gamma_0 \sim 10^4\) for example, the characteristic observed pulse width could be as small as \(\sim 10^{-3}\). This seems interesting when compared with the inferred Gaussian width of ~0.002 for the additional γ-ray (phasogram) component in the range (10–80) GeV around P2 (Abdalla et al. 2018).

3. Conclusion

The generation of VHE γ-rays in fast pulsars is still an open issue (e.g., Bednarek 2012; Mochol & Pétri 2015; Hirotani 2015; Osmanov & Rieger 2017; Harding et al. 2018). The latest H.E.S.S. observations of the Vela pulsar in the sub-20 GeV to 100 GeV regime have now revealed pulsed γ-rays from its P2 peak at high significance, and together with an updated analysis of Fermi-LAT data suggest the emergence of a second, new hard VHE component above 50 GeV in the leading wing (LW2) of P2 (Abdalla et al. 2018).

Motivated by this, we analyzed the potential role of centrifugal acceleration in the generation of pulsed VHE emission in the magnetosphere of the Vela pulsar. Our results show that IC up-scattering of thermal photons by rotationally accelerated electrons close to the light cylinder could lead to a hard (yet falling) power-law-like VHE contribution that reaches into the teraelectronvolt regime and in the case of LW2 could become apparent above ~50 GeV. Future observations with increased sensitivity will be important to better probe its spectral characteristics and to eventually allow a clear identification. Along with the Crab pulsar (Osmanov & Rieger 2017), this could be the second case where rotationally driven γ-ray emission turns out to be important to fully understand the VHE emission in young pulsars.

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References

Zabalza, V. 2015, 34th Int. Cosmic Ray Conf. (ICRC2015), 34, 922