JITTER RADIATION MODEL OF THE CRAB GAMMA-RAY FLARES

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ABSTRACT

The gamma-ray flares of the Crab nebula detected by the Fermi and AGILE satellites challenge our understanding of the physics of pulsars and their nebulae. The central problem is that the peak energy of the flares exceeds the maximum energy $E_c$ determined by synchrotron radiation loss. However, when turbulent magnetic fields exist with scales $\lambda_B$ smaller than $2\pi mc^2/eB$, jitter radiation can emit photons with energies higher than $E_c$. The scale required for the Crab flares is about two orders of magnitude less than the wavelength of the striped wind. We discuss a model in which the flares are triggered by plunging the high-density blobs into the termination shock. The observed hard spectral shape may be explained by the jitter mechanism. We make three observational predictions: first, the polarization degree will become lower in flares; second, no counterpart will be seen in TeV–PeV range; and third, the flare spectrum will not be harder than $\nu F_\nu \propto \nu^4$.

Key words: gamma rays: stars – ISM: individual objects (Crab nebula) – ISM: supernova remnants – radiation mechanisms: non-thermal – turbulence

Online-only material: color figures

1. INTRODUCTION

The Crab nebula has been known as a luminous celestial object and has been regarded as a stationary emitter except for a secular change due to expansion. Recently, strong flares were detected five times in the range $> 100$ MeV by the AGILE (Tavani et al. 2011) and Fermi (Abdo et al. 2011; Buehler et al. 2012; Ojha et al. 2012) satellites. The flares occur about once every six months, the flux doubling timescale is around 8 hr, and its duration time is a few weeks. The peak energy is as high as 375 MeV, which is a challenge for the standard scenario of pulsar wind nebulae (Buehler et al. 2012). When electrons/positrons are accelerated on a gyrotimescale, synchrotron radiation limits the attainable energy (see, e.g., Kirk & Reville 2010), and the maximum energy of synchrotron radiation is $\sim 100$ MeV. Since there seem to be no counterparts in other energy ranges, they should involve only the highest energy particles. In fact, the flare of 2011 April shows very hard spectrum with the photon index $\gamma_F = 1.27 \pm 0.12$ (Buehler et al. 2012). The peak flux amounts to $(186 \pm 6) \times 10^{-7}$ cm$^{-2}$ s$^{-1}$, 30 times larger than the quiescent one. The isotropic luminosity amounts to $4 \times 10^{46}$ erg s$^{-1}$, corresponding to 1% of the spin-down luminosity of the Crab pulsar. The size of the emission region of the flares should be as small as $c t_{\text{flare}} \sim 10^{15}$ cm or $c t_{\text{dur}} \sim 3 \times 10^{16}$ cm, where $t_{\text{flare}}$ is the fluctuation timescale estimated from flux changes and $t_{\text{dur}}$ is the duration timescale of the flares. Both sizes are very small compared to the circumference of the termination shock $2\pi r_s \sim 2 \times 10^{14}$ cm, where $r_s$ is the radius of the termination shock from the Crab pulsar. It is notable that such a large amount of energy is concentrated in a small region.

Although several models have been proposed to overcome the crucial problem of $E_c$, a consensus has not been achieved. The obvious possibility is the relativistic beaming effect. In the standard scenario of pulsar wind nebulae (e.g., Kennel & Coroniti 1984), the bulk speed of the nebula region is nonrelativistic, but a possibility of the emission regions having relativistic speed has been discussed from various aspects (Komissarov & Lyutikov 2011; Bednarek & Idec 2011; Yuan et al. 2011; Kohri et al. 2012; Clausen-Brown & Lyutikov 2012). Another possibility is a separation between the acceleration region and emission region (Uzdensky et al. 2011; Cerutti et al. 2012). Those authors considered the acceleration by the electric field on a reconnection sheet. The magnetic field on the reconnection sheet is much weaker than outside the sheet, and electrons can be accelerated by the electric field suffering from much weaker radiation loss and achieve a larger Lorentz factor. In a somewhat different viewpoint, Bykov et al. (2012) considered effects of inhomogeneities of the magnetic field strength. The highest Lorentz factor of the electrons is limited by the mean strength of the magnetic field, and the highest energy emission comes from small regions where the magnetic field is strongest. The spatial scale of the acceleration region is the same order of the Larmor radius of the highest energy electrons $r_L \sim 2 \times 10^{17} (\gamma/10^4) (B/10^{-4} \text{G})^{-1}$ cm, while the scale of the emission region is as small as $c t_{\text{flare}} \sim 10^{15}$ cm or $c t_{\text{dur}} \sim 3 \times 10^{16}$ cm. If the magnetic field varies by a factor of 3 in a small region, the emission energy can be higher than $E_c$ in this case.

A common feature of these models is that the radiation process is considered to be synchrotron radiation. In contrast, we consider yet another possibility that the magnetic fields become turbulent on very small scales, and that the radiation process changes from synchrotron radiation to jitter radiation. The photon energy of jitter radiation can be higher than $E_c$ in this situation (Fleishman 2006). For the jitter radiation, the typical frequency is determined by the scale $\lambda_B$ of the turbulent magnetic field. We suppose that this scale is much smaller than $2\pi mc^2/eB$ and that the electrons move approximately in a straight line. The typical frequency is $\gamma^2$ times the inverse of the timescale that the electrons move across $\lambda_B$, and

$$\omega_B \sim \gamma^2 \frac{2\pi c}{\lambda_B}. \quad (1)$$

Therefore, photons with frequencies higher than $\gamma^2 eB/mc$ can be emitted if the spatial scale of the turbulent magnetic field is smaller than $2\pi mc^2/eB$. 
In this paper, we discuss the flare model based on jitter radiation. In Section 2, we explain the possible ways to create the flares by jitter radiation and discuss the flare energetics and spectra. In Section 3, we discuss differences between our model and other models. We summarize the paper in Section 4.

2. JITTER RADIATION

2.1. Small-scale Turbulence

The jitter radiation is the radiation from a relativistic particle moving in a random magnetic field with the spatial coherence scale shorter than the typical synchrotron photon formation length (Medvedev 2000). We assume that the turbulent magnetic field is isotropic. When $\lambda_B < 2\pi mc^2/eB$, in other words, when the strength parameter

$$a \equiv eB\lambda_B/(2\pi mc^2)$$

is smaller than 1, jitter approximation is valid (Medvedev et al. 2011; Teraki & Takahara 2011). Using the condition for jitter approximation of $a < 1$, we can write the strength of magnetic field of the emission region as

$$B < 1 \times 10^{-3} \left(\frac{\lambda_B}{10^7 \text{ cm}}\right)^{-1} \text{G.}$$

We suppose that the acceleration site for the flares is near the shock front. We tentatively assume that the magnetic field becomes turbulent in a small part of the acceleration region, though we consider later that their sizes are of the same order. The Lorentz factor of accelerated electrons that emit the highest energy synchrotron photons $\sim 100$ MeV in a quiescent state is thought to be $\sim 10^{10}$ and the average magnetic field strength is $\sim 10^{-4}$ G (Kennel & Coroniti 1984; De Jager & Harding 1992; Atoyan & Aharonian 1996; Tanaka & Takahara 2010). The required scale of turbulence to meet the condition $a < 1$ is $\lambda_B < 10^8$ cm when magnetic field strength is $10^{-4}$ G. On the other hand, the required scale to emit flare photons with energy $\sim 400$ MeV by the highest energy electrons through the jitter radiation, the required scale of turbulent magnetic field is $\sim 3 \times 10^7$ cm.

We note that the wavelength of the striped wind of the Crab pulsar ($\lambda_{sw} \equiv c \times 33 \text{ ms} \times 10^9$ cm) is around the required length. Our picture of the flares is expressed as follows. When alternating magnetic fields are injected into the acceleration site, fluctuations with scales shorter than $\lambda_{sw}$ are generated through compression or transformation to some type of waves. The highest energy electrons feel the small-scale magnetic fields and radiate high energy photons by the jitter mechanism. In the quiescent state, this mechanism may not work because the density in the pulsar wind is very low, and the small-scale turbulent field is suppressed, as we see in the next paragraph. Here, we consider how the small-scale magnetic field can be generated when the flares occur. In general, the pulsar wind fluctuates temporarily and spatially. For example, the Crab pulsar is known to emit very energetic radio pulses, called “Giant Radio Pulse” (GRP) about once every several thousand (e.g., Lundgren et al. 1995). This suggests that there may be large density fluctuations in the magnetosphere. Furthermore, from the observations of these GRPs, it has been argued that the dispersion measure fluctuates largely, and these fluctuations cannot be explained by considering the density fluctuations of the interstellar medium alone. Therefore, it is suggested that there are large density fluctuations in the Crab nebula (Kuz’min et al. 2008, 2011). From these observations, it is quite natural to suppose that there are density fluctuations in the wind region. We advocate a model that the plunging of a high-density blob into the termination shock triggers a flare. We note, however, that the flares are not directly the same events as GRP (Mickaliger et al. 2012).

Next we compare the wavelength of striped wind and the typical scales of plasma in the comoving frame, and consider the conditions for survival of small-scale magnetic fields. Although the striped wind itself is a non-propagating entropy mode, the existence of high-density blobs and moderate reconnection may generate electrostatic and electromagnetic modes on a somewhat shorter wavelength than $\lambda_{sw}$. We may consider various modes, for example, the electron Bernstein mode, which is the electrostatic wave in a thermal plasma (Bernstein 1957), but we do not specify the type of plasma turbulence. When the inertial length is longer than $\lambda_{sw}$, the electromagnetic modes can survive, while the short-scale electrostatic mode may decay. To estimate the typical scale of the survival of the longitudinal modes, we use the value of inertial length. First we consider it in the upstream, i.e., wind region. The Debye length is very small compared to the inertial length because the plasma is cold when the reconnection is moderate. The inertial length $c/\omega_{pe}$ can be estimated given the comoving number density. The spin-down luminosity is expressed by

$$L_{sd} = 4\pi r_u^2 n \Gamma u c^3 (1 + \sigma) \sim 6 \times 10^{38} \text{ erg s}^{-1},$$

where $r_u = 3 \times 10^7$ cm, $n$ is the comoving number density, $\Gamma = 10^6$ (Kennel & Coroniti 1984) or $\Gamma = 7 \times 10^3$ (Tanaka & Takahara 2010) is the bulk Lorentz factor of the pulsar wind, $u$ is the radial four velocity, and $\sigma$ is the ratio of magnetic to kinetic energy flux. In general, $\sigma$ is thought to be much smaller than 1 at the shock region ($\sigma \sim 0.003$ is the best-fit value in Kennel & Coroniti 1984). We adopt this assumption, and neglect $\sigma$ in Equation (4). When we adopt the value of the bulk Lorentz factor by Tanaka & Takahara (2010), we get the comoving density $n \sim 4 \times 10^{-10} \text{ cm}^{-3}$ and the value of inertial length

$$\left(\frac{c}{\omega_{pe}}\right)_{u,TT} \sim 3 \times 10^{10} \text{ cm.}$$

When we adopt $\Gamma = 10^6$ (Kennel & Coroniti model), the comoving density becomes smaller. Using Equation (4), we get $n \sim 2 \times 10^{-14} \text{ cm}^{-3}$, and we obtain

$$\left(\frac{c}{\omega_{pe}}\right)_{u,KC} \sim 3 \times 10^{12} \text{ cm.}$$

On the other hand, the comoving wavelength of striped wind is

$$(\Gamma \lambda_{sw})_{TT} \sim 1 \times 10^{12} \text{ cm},$$

$$(\Gamma \lambda_{sw})_{KC} \sim 2 \times 10^{14} \text{ cm.}$$

Therefore, the inertial length is shorter than the wavelength of the striped wind. From the estimation described above, we can see that the small-scale turbulence can survive in the wind region.

Next we consider the parameters for downstream. We do not consider the possibility that the downstream plasma has a
bulk relativistic speed. The inertial length and Debye length are comparable at relativistic temperatures. We adopt the value of a typical Lorentz factor $\gamma = 7 \times 10^3$ (the Tanaka & Takahara model) and $\gamma = 10^6$ (the Keneel & Coroniti model). Then we obtain the inertial length

$$\left(\frac{c}{\omega_{pe}}\right)_{d,TT} \sim 3 \times 10^{10} \text{ cm}, \quad (9)$$

$$\left(\frac{c}{\omega_{pe}}\right)_{d,KC} \sim 3 \times 10^{12} \text{ cm}. \quad (10)$$

The wavelength of the striped wind is compressed by a factor of a few $\times \Gamma$ times compared to the comoving wavelength upstream. Therefore, the typical scale of magnetic field is

$$\langle \lambda_{sw}\rangle \sim 3 \times 10^8 \text{ cm}. \quad (11)$$

From the estimation above, we see that the small-scale turbulence decays far downstream. We note that near the shock front or in the shock transition region the plasma is not completely thermalized. Therefore, the small-scale turbulence can survive in some measure there.

Generally, when the Debye length is much larger than $\lambda_{sw}$, the longitudinal mode would disappear rapidly. However, when the dense blob enters the shock front, the inertial length becomes shorter and small-scale turbulence tends to survive longer. The density required for the survival far downstream is $10^5$ times larger than the mean density $n$, but even when the density contrast is less extreme, the short wavelength turbulence required for the flares can exist in the shock transition region.

Summarizing this subsection, jitter radiation can produce the flare when the small-scale turbulence survives in the shocked dense blob, and the typical scale of turbulence is consistent with the typical frequency of the flares. We propose the flare model in which the high-density blob plunges into the termination shock, an entropy mode is compressed or transformed into some other waveform in the shock transition region, and the accelerated electrons move in this kind of turbulent field and radiate the highest energy photons by jitter mechanism.

2.2. Energetics

Now that we have shown that the peak energy higher than $E_c$ can be explained by jitter radiation, we next examine the energetics of flares. First we note that the energetics problem is very difficult to solve and has not been much addressed in previous models. The scale of the emission region is constrained by the observed fluctuation timescale as $c\tau_{\text{fluc}} \sim 10^{15} \text{ cm}$ or by the duration timescale as $c\tau_{\text{d}} \sim 3 \times 10^{16} \text{ cm}$. It is very difficult to concentrate 1% of the spin-down luminosity on this small region, compared to the circumference of the termination shock $\sim 2 \times 10^{15} \text{ cm}$, in either case. We discuss the energetics by considering the size of the emission region and the density of radiating particles in it. The Crab nebula is not spherically symmetric as is seen in the X-ray image by the Chandra X-ray Observatory (Gaensler & Slane 2006). It is possible that the emission regions of 100 MeV gamma rays are patchy, but we do not resolve the Crab nebula at 100 MeV gamma rays. We assume that the shape of the emission region is a ring as drawn in Figure 1, for simplicity. When the nebula is quiescent, the radial thickness is determined by synchrotron cooling. To estimate the radial thickness, we suppose that the acceleration site is located only near the shock front, and the electrons return to the shock front on gyrotime. If we assume the standard value of the strength of magnetic field $B = 300 \mu \text{G}$ (Kennel & Coroniti 1984), and consider the fact that cooling limits the attainable energy as $\gamma \sim 6 \times 10^5 (B/(3 \times 10^{-4} \text{ G}))$, we obtain the radial thickness of the ring as $\tau_{r} \sim 3 \times 10^{16} \text{ cm}$. When we assume $B = 85 \mu \text{G}$ (Tanaka & Takahara 2010), the thickness is three times larger. We assume that the injection site of the highest energy electrons is on the equatorial plane, so the ring height is also constrained by gyroradius of highest energy electrons. The radius of the termination shock is $3 \times 10^{17} \text{ cm}$, so the radial thickness and height of the 100 MeV ring is a few $\times 10\%$ of the radius.

Next, we estimate the parameters in the emission region in the flare state. First, we examine the case when the scale of the blob is $c\tau_{\text{fluc}} \sim 10^{15} \text{ cm}$, and the single blob becomes the emission region for the flare. We assume that the blob moves on the equatorial plane, so a part of the ring becomes the emission region of flare. If we assume that the strength of magnetic field in the blob is the same as in the other region, the radial thickness of the jitter emission region cannot be determined by synchrotron cooling because the Larmor radius of the highest energy electrons $3 \times 10^{16} \text{ cm} (B/(3 \times 10^{-4} \text{ G}))^{-3/2}$ is larger than the blob size $c\tau_{\text{fluc}}$. The acceleration region is larger than the jitter emission region and the size of emission region is determined by blob size in this picture. However, this picture does not work for flare models. The energy distribution of electrons at flare states is very hard and different from that of the quiescent state. The acceleration process in the acceleration region of the highest energy electrons that emit flare photons is different from the other region. We assume that a dense blob enters in the termination shock region, and implicitly assume that the other region is undisturbed. Then the acceleration process outside the blob should be the same as in the quiescent state. Therefore, it is more natural that the magnetic field in the blob is stronger than the mean magnetic field strength and that the acceleration process is also different in the flare states to produce the highest energy electrons with a very hard spectrum. Thus, the cutoff energy of accelerated electrons should be smaller because of the strong magnetic field. Since the size of acceleration region is limited by the blob size,
the required strength of the magnetic field is $3 \times 10^{-3}$ G to make $r_s = c t_{\text{fluc}}$, and the maximum Lorentz factor is limited by radiation loss and becomes smaller to $\sim 2 \times 10^9$. Therefore, the required wavelength of the turbulent field becomes $10^6$ cm to emit 400 MeV photons. This constraint may seem very tight, but it is not improbable. From this consideration, the volume of the blob is $10^{45}$ cm$^3$, and the emission region of the flare is about $2 \times 10^6$ times smaller than in quiescent state because the volume of 100 MeV ring is (circumference) $\times$ (radial thickness) $\times$ (height) $= 2 \times 10^{51}$ cm$^3$.

To estimate the blob size, we used the time scale of flux fluctuation of eight hours up to here. We then consider another model that the blob has an internal structure as depicted in Figure 2, and flux fluctuation comes from it, thus the size constraint can be alleviated. The blob size is estimated $c t_{\text{fluc}} = 3 \times 10^{16}$ cm from the duration time of the flare, and the typical scale of denser regions is $c t_{\text{fluc}} = 10^{15}$ cm. The mean magnetic field strength is $3 \times 10^{-4}$ G, by equating Larmor radius of highest energy electrons and $c t_{\text{fluc}}$. The Lorentz factor of the highest energy electrons is determined by the magnetic field strength as $\gamma \sim 6 \times 10^9$, and the required wavelength of turbulent field to emit 400 MeV photon is estimated as $10^7$ cm. The size of the blob is $3 \times 10^{16}$ cm, which is the same as the thickness of the 100 MeV ring in the quiescent state for the standard magnetic field strength. Therefore the blob volume is only about $10^2$ times smaller than the 100 MeV ring.

Next we consider the required number density of the highest energy electrons in the blob to reproduce the flare luminosity. If the acceleration is the same as in the quiescent state, the number density of the highest energy electrons may not be as large as $10^6$ times the number density of the highest energy electrons in the quiescent state. However, the energy distribution of accelerated electrons is very hard, so the number of the highest energy electrons can be $10^6$ times larger than in the quiescent state. Therefore, the flare luminosity can be explained by this model if the mean density in blob fulfills the condition of the survival of the small-scale turbulence. Here, we note that the flare luminosity is 1% of the spin-down luminosity, so the asymmetry of the pulsar wind must be very high in this model.

Next, we examine the constraint on the scenario of inhomogeneous blob of a size $c t_{\text{fluc}}$. The blob volume is only $10^2$ times smaller than the 100 MeV ring, and we assumed that the magnetic field strength is the same order as the one of quiescent state ($3 \times 10^{-4}$ G), so the maximum Lorentz factor of the electrons is the same as in the other region. The required number density of highest energy electrons in the blob is about $10^2$–$10^3$ times larger than the mean density of highest energy electrons. The flare luminosity can be obtained by considering the hardness of the electron energy distribution which is calculated from the observed flux alone, and the high number density of electrons would help to accomplish the large luminosity of flare. In short, while the small homogeneous blob scenario is not impossible, the large inhomogeneous blob scenario is more plausible.

### 2.3. Spectrum

The observed spectra of flares indicate that the energy distribution of electrons is very hard. As is discussed in the previous subsection, the hard energy distribution of electrons is also required to solve the energetics. If the electrons take a power-law energy distribution, the power-law index $p$ of electrons $(dN/dE \propto E^{-p})$ can be estimated from the photon index. However, when the strength parameter $a < 1$ and when either $p < 1$ or $p < 2\mu + 1$, the photon index around 100 MeV can be determined by jitter mechanism, where $\mu$ is the power-law index of isotropic turbulent magnetic field ($B^2(k) \propto k^{-\mu}$). The spectrum of flare component is fitted by a power-law plus cutoff, and the time integrated power-law index is $\gamma_F = 1.27 \pm 0.12$ (Buehler et al. 2012). Clausen-Brown & Lyutikov reexamined the time resolved spectrum in Buehler et al. (2012) and obtained the photon index in the most luminous period as

$$\gamma_F = 1.08 \pm 0.16.$$  

(12)
If the index is supposed to reflect the energy distribution of electrons, the time integrated power-law index is $p = 1.54 \pm 0.24$ and time resolved one (in the most luminous state) is $p = 1.16 \pm 0.32$, because $\gamma_F = (p + 1)/2$. It is very hard and inconsistent with the power-law index $p = 2.5$ at injection in the quiescent state (Tanaka & Takahara 2010). Additionally, the hard energy distribution is consistent with the observation that no counterpart of the flares has been detected in other wavelengths. Thus, the particle acceleration in the blob is expected to be different from the other region. For example, a stochastic acceleration process may play a crucial role in making the hard electron energy distribution in a short time (see, e.g., Hoshino 2012).

The hard photon index can be interpreted as the reflection of hard power-law index of electron energy distribution, but obtaining the value $p \sim 1$ is somewhat difficult (Clausen-Brown & Lyutikov 2012). We show another interpretation of these spectral indices by using the theory of jitter radiation on the assumption that the accelerated electrons follow a stochastic acceleration process.

First, we discuss the difference from their model. They assumed that the size of the acceleration site is much larger than the emission region, and the acceleration mechanism in the quiescent state and flare state is identical. If the energy distribution of electrons remains unchanged in the flare state, the spectra in the 100 MeV range cannot become harder than the spectrum in MeV range in the quiescent state. This does not seem to match our observations. In contrast, we consider that the acceleration site should have a size similar to the blob size, and the acceleration mechanism is different in the flares because the observed spectrum is very hard. When the electron energy distribution is very hard $(p \ll 1)$, the photon index $\gamma_F = 1$ can be naturally explained by jitter mechanism. Bykov et al. deal with the problem assuming that the emission region is one-dimensional for radial direction, and do not consider the energetics explicitly in their paper. The authors consider that the radial length of the emission region is the same as the quiescent state $(2 \times 10^{16} \text{ cm})$, and there are the blobs randomly distributed with the 1% scale $(\sim 10^{14} \text{ cm})$ having a stronger magnetic field. The length is consistent with the observed timescale of the flares. The scale corresponding to the single pulse of flare must be smaller than $10^{15} \text{ cm}$. The solid angle of the emission region can be constrained by the duration time of flare. Therefore, the predicted luminosity is a few dozen times smaller than the observed one. While Bykov et al. predicted that the polarization degree would enhance during the flare, our model predicts the converse prediction. The polarization degree would be very low during the flare, because the gamma rays are emitted in the turbulent field by the jitter mechanism.

The most popular interpretations of the Crab flares are Doppler boost models. While the Doppler boost model predicts that the TeV–PeV flare would accompany the 100 MeV flare, our model does not predict such a correspondence between GeV and TeV–PeV. In our model, the increase of the highest energy electrons and frequency shift collaborate to create the flare. Therefore, the required total number of the highest energy electrons is only a few times larger than the quiescent state. In the TeV–PeV range, since there are no frequency shifts, inverse Compton scattering by the highest energy electrons is in the Klein–Nishina regime so that only a very weak bump will appear in the PeV range.

The hard spectrum of flares is one of the difficult features to interpret. Clausen-Brown & Lyutikov explained this hard spectrum by very hard electron energy distribution near the radiation reaction limit. They assumed an acceleration time much shorter than escaping time and considered radiation loss. The electrons pile up near the maximum energy. They commented that the pile-up scenario could explain the observed spectral energy distribution by tuning the acceleration timescale. If the acceleration time is much shorter than the fluctuation time of flare, the distribution becomes monoenergetic, and spectrum becomes intrinsic one $\gamma_F = 2/3$ for synchrotron radiation or $\gamma_F = 1$ for jitter radiation. Our model does not require the

**Figure 3.** Radiation spectrum of jitter radiation by monoenergetic electrons for $a < 1$. (A color version of this figure is available in the online journal.)

3. DISCUSSION

3.1. The Difference from Other Models and Predictions

We have considered inhomogeneities of the emission region. Bykov et al. also considered inhomogeneous emission regions. First, we discuss the difference from their model. They assumed that the size of the acceleration site is much larger than the emission region, and the acceleration mechanism in the quiescent state and flare state is identical. If the energy distribution of electrons remains unchanged in the flare state, the spectra in the 100 MeV range cannot become harder than the spectrum in MeV range in the quiescent state. This does not seem to match our observations. In contrast, we consider that the acceleration site should have a size similar to the blob size, and the acceleration mechanism is different in the flares because the observed spectrum is very hard. When the electron energy distribution is very hard $(p \ll 1)$, the photon index $\gamma_F = 1$ can be naturally explained by jitter mechanism. Bykov et al. deal with the problem assuming that the emission region is one-dimensional for radial direction, and do not consider the energetics explicitly in their paper. The authors consider that the radial length of the emission region is the same as the quiescent state $(2 \times 10^{16} \text{ cm})$, and there are the blobs randomly distributed with the 1% scale $(\sim 10^{14} \text{ cm})$ having a stronger magnetic field. The length is consistent with the observed timescale of the flares. The scale corresponding to the single pulse of flare must be smaller than $10^{15} \text{ cm}$. The solid angle of the emission region can be constrained by the duration time of flare. Therefore, the predicted luminosity is a few dozen times smaller than the observed one. While Bykov et al. predicted that the polarization degree would enhance during the flare, our model predicts the converse prediction. The polarization degree would be very low during the flare, because the gamma rays are emitted in the turbulent field by the jitter mechanism.

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**Figure 3.** Radiation spectrum of jitter radiation by monoenergetic electrons for $a < 1$. (A color version of this figure is available in the online journal.)
tuning of acceleration time and predicts that the flare spectrum will not be harder than $vF_v \propto v^1$.

3.2. The Acceleration and Scatterers

Kirk & Reville (2010) argued that jitter radiation cannot emit photons with energy higher than the critical synchrotron energy in the diffusive shock acceleration (DSA) scenario. In their analysis, they assumed that the scatterer (magnetic field fluctuation) is a single population. For $a < 1$, particles experience ballistic transport and take a longer time to come back to the shock than the gyrote. Therefore, the acceleration time becomes longer, so the maximum energy of electrons becomes smaller, and radiation frequency is smaller than that for $a > 1$ despite taking into account the jitter mechanism. Conversely, we argue that the jitter mechanism can emit higher energy radiation than synchrotron one. The reason for apparently inconsistent conclusions lies in the difference of the situations. We implicitly assumed the existence of multi populations of scatterers. Although we do not specify the acceleration mechanism, we suppose that the large-scale scatterers exist, too. The acceleration time depends on the large-scale (as large as Larmor radius) scatterers, so the acceleration time is not as long. Therefore, our model does not contradict their conclusion. In fact, the situation with two populations of scatterers is considered by Reville & Kirk (2010), and jitter component emerges over the synchrotron cutoff. Thus, the photon energy of jitter component can be higher than that of synchrotron component when there are multi population of scatterers.

4. SUMMARY AND CONCLUSION

We propose a model that explains the flares of the Crab nebula over the 100 MeV by jitter radiation. The wavelength of striped wind of the Crab pulsar is about two orders of magnitude longer than the required scale of turbulent fields to emit photons with energy $E > E_c$ by jitter mechanism. A high-density region is required for the existence of the small-scale turbulence. It is suggested that there are large density fluctuations in the Crab pulsar magnetosphere and nebula. Therefore, we consider that there are high-density blobs in the pulsar wind region. The blobs plunge into the termination shock, generate the short wavelength turbulence of electromagnetic field, and accelerated electrons radiate gamma-ray emission by jitter mechanism in the blob. The required strength of the mean magnetic field in the blob is 10 times larger, and the number density of the highest energy electrons in the blob is $10^6$ times larger than in the quiescent state to reproduce the 2011 April flare by the homogeneous blob model for which the size of the blob is $c t_{\text{fluc}} \sim 3 \times 10^{15}$ cm. When we adopt the inhomogeneous blob model, for which the size of the blob is $c t_{\text{fluc}} \sim 3 \times 10^{16}$ cm, the required magnetic field strength is as large as that of the quiescent one, and the number density of the highest energy electrons is about $10^2$--$10^3$ times larger than in the quiescent state. The required high density of the highest energy electrons in the blob is consistent with our assumption that the high-density blobs trigger flares and hard energy distribution of electrons which is implied by the observed spectra. The very hard photon index $\gamma_T = 1.08 \pm 0.16$ of 2011 April flare in the brightest state is consistent with the intrinsic photon index of jitter radiation for $a < 1$. We make following three predictions for the future Crab flares: first, the polarization degree will become lower in flare state; second, no counterpart will be seen in TeV–PeV range; and third, the flare spectrum will not be harder than $vF_v \propto v^1$.

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