Possibility of Ultra High-Energy Cosmic Rays from the Giant Flare in SGR 1806−20

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Abstract

On 2004 December 27, a giant flare from the soft gamma repeater 1806−20 was observed. The radiation mechanism of the initial peak of the flare would be controversial. In this letter we point out that very high-energy cosmic rays would be produced in the case that the flare was caused by internal shocks, as is usually considered for gamma-ray bursts. The highest energy of cosmic rays can reach $10^{19}$ eV, if the Lorentz factor of the shocks is sufficiently high. Future observations of cosmic rays will inform us about the mechanism of the giant flare.

Key words: cosmic rays —gamma-rays: bursts —pulsars: individual (SGR 1806−20)

1. Introduction

Soft gamma repeaters (SGRs) are X-/gamma-ray transient sources that show periods of bursting activity separated by long intervals of quiescence. They are galactic and LMC populations, and are considered to originate from neutron stars with intense ($\lesssim 10^{15}$ G) magnetic fields (magnetars) (Thompson, Duncan 2001).

On 2004 December 27, a giant flare from SGR 1806−20 was observed by several detectors (Hurley et al. 2005; Terasawa et al. 2005; Palmer et al. 2005; Mazets et al. 2005). The initial peak of the giant flare had $\sim 0.6$ s duration. The isotropic-equivalent energy would have been $E_{\gamma} \sim 10^{46-47}d_{15}^{-2}$ erg and the peak luminosity in the first 125 ms would have been $L_{\gamma} \sim 10^{47}d_{15}^{-2}$ erg s$^{-1}$, where $d_{15} = d/15$ kpc, and $d$ is an uncertain distance to the source (Corbel, Eikenberry 2004; Cameron et al. 2005; McClure-Griffiths, Gaensler 2005).

In the context of the magnetar model (Thompson, Duncan 2001), the giant flare arose
from a hot expanding fireball, which was only weakly polluted by baryons. The initial optical depth for pair creation is extremely large in this model. As a result, this radiation-pair plasma expands relativistically. The Lorentz factor, $\gamma$, increases in proportion to the radius, $R$, and the temperature in the comoving frame decreases as $T \propto R^{-1}$ (Piran et al. 1993). The photons decouple when the temperature decreases below $\sim 20$ keV (Nakar et al. 2005). At this stage the Lorentz factor becomes $\sim 10$, and the radius becomes $R \sim 10R_0$, where $R_0 \sim 10$ km is the size of the magnetar. The photon temperature that we observe is the initial temperature independently of $\gamma$ at the decouple stage because of the relativistic blue-shift. The predicted photon spectrum from this “pure radiation-pair fireball model” is, therefore, a quasi-blackbody with a temperature of $T \sim 200$ keV (Hurley et al. 2005). The time-resolved (125 ms) energy spectrum from the RHESSI particle detector is consistent with that of a black body whose temperature is $\sim 200$ keV, though the main RHESSI spectroscopy detectors were saturated during the peak (Boggs et al. 2005).

However, there are so many ambiguities that one cannot confirm the above picture. The spectrum of the initial peak of the giant flare is not yet well determined. Hurley et al. (2005) reported on the cooling blackbody spectrum, which is consistent with the pure radiation-pair fireball model. However, Mazets et al. (2005) derived a power-law spectral shape ($\alpha = -0.7$) with an exponential cut-off at 800 keV. There was another independent measurement, resulting in a power-law spectrum ($\alpha = -0.2$) with an exponential cut-off at 480 keV (Palmer et al. 2005). Furthermore, another giant flare in SGR 0526$-$66 may also have had a nonthermal spectrum (Fenimore et al. 1996). Therefore, we still have no definite evidence to interpret that the flare on 2004 December 27 was a thermal one.

Another ambiguous point is the initial speed of the outflow or, almost equivalently, the baryon richness. The radio afterglow detected after the giant flare may give us some hints to solve this problem (Cameron et al. 2005; Gaensler et al. 2005; Taylor et al. 2005). Wang et al. (2005) showed that the same mechanism as established for gamma-ray burst (GRB) afterglows (decelerating-outflow model) can explain the radio afterglow of the giant flare, suggesting that the initial outflow was highly relativistic. On the other hand, Granot et al. (2005) and Gelfand et al. (2005) succeeded to fit the radio afterglow by their model, in which the outflow is initially non-relativistic and contains baryonic material of more mass than the $10^{24}$ g ejected from the magnetar, itself. The baryon amount in this picture, at first glance, may contradict the optically thin emission of the flare. Therefore, some authors (Eichler 2005; Dai et al. 2005) propose multi-component models, in which relativistic (baryon-poor) components and non-relativistic (baryon-rich) components outflow from the surface.

Jet collimation has been suggested by Yamazaki et al. (2005) (Y05) through reproducing the observed light curve of the initial peak observed by GEOTAIL with a 5.48 ms time resolution (Terasawa et al. 2005). Using a simple emission model for relativistically moving matter (Yamazaki et al. 2003), they derived an upper limit of the jet opening half-angle of 0.2 rad. In
this model the initial peak in the giant flare arises from internal shocks in relativistic jets. The radius, \( R \), where the shock front starts to emit photons, is estimated to be \( R = 2.6 \times 10^8 \gamma^2 \) cm, which is much larger than the radius, \( \gamma R_0 \sim 10^7 \) cm, derived from the pure radiation-pair fireball model. Considering the opening half-angle of the jet, \( \Delta \theta < 3/\gamma \) (Y05), the collimation-corrected energy of the jet may be \( 10^{45} \) erg if the radiation efficiency is assumed to be 10%. The observed proper motion of the centroid of a radio image (Taylor et al. 2005) may support the collimated outflow. The relativistic jet is significantly decelerated due to the sideways expansion within ten minutes after the giant flare (Rhoads 1999; Sari et al. 1999; Yamazaki et al. 2005), so that the radio image expands non-relativistically (Taylor et al. 2005). Introducing a non-relativistic component besides the relativistic jet, the observed expansion law of the radio image may also be explained (Dai et al. 2005).

Therefore, there are three controversial questions concerning this event: 1) Are there baryonic flows during the initial stage? 2) Are there relativistic components in the baryonic flows? 3) Does the flow have a jet-collimated structure? We cannot, at present, definitely answer these questions. In this paper we show that observations of ultra-high-energy cosmic rays (UHECRs) or neutrinos may resolve the above-mentioned problems (Eichler 2003; Ioka et al. 2005). Ioka et al. (2005) extensively discussed the possibility of photopion production and the resultant neutrino detection from this event. On the other hand, our discussion places emphasis on the detection possibility of UHECRs delayed from the giant flare, based on the model in Y05, which can explain the light curve of this event.

If there is a shocked outflow of baryons, the shock waves may accelerate non-thermal protons to very high energies. As for extragalactic GRBs, Waxman (1995); Vietri (1995) pointed out that GRB is a candidate of UHECR sources, and Milgrom, Usov (1995) discussed possible observations of UHECRs. In this paper we discuss the possibility of UHECR production in the giant flare of SGR 1806–20. Combining neutrino observations, UHECR detections may provide information on the above questions 1) and 2). In section 2 we obtain the maximum energy of UHECRs accelerated in shock waves based on the jet model of Y05. In section 3 the expected number flux of UHECRs, which depends on the structure of the galactic magnetic fields, is discussed. Our conclusions are summarized in section 4.

2. Maximum Energy of Cosmic Rays

In this section we adopt the jet model of Y05 and estimate the maximum energy of cosmic rays that we can observe. We expect that even another internal shock model may predict similar maximum energies to ours, as long as the assumed energy and time-scale of the flare are close to ours (see e.g. Eichler 2005).

In the model of Y05 a shell moving with the Lorentz factor, \( \gamma \), emits gamma rays from \( R = R_i = 2.6 \times 10^8 \gamma^2 \) cm to \( R_c \sim 10 R_i \). The duration in the comoving frame is \( (R_c - R_i)/(c\gamma) \sim R_c/(c\gamma) \), which corresponds to the shell crossing time scale. Therefore, the shell width in the
observer frame is about $R_e/\gamma^2$, while the shell width used conventionally in the GRB models is $R_i/\gamma^2$, which implies $R_e \sim R_i$. Thus, the shell width obtained from the GEOTAIL light curve is relatively thick. As a result, the physical conditions around $R \sim R_i$ and $R \sim R_e$ are different.

It is difficult to estimate the magnetic field in the shell, because the light curve provides information only on the kinematic properties. The plasma in the shell coming from the magnetar may be strongly magnetized. A part of the energy of the magnetic field may be expended in the acceleration phase, while various plasma instabilities may enhance the field, as is discussed by Medvedev, Loeb (1999) for GRBs. Though we recognize the above difficulties, we assume that the energy density of the magnetic field is proportional to the photon energy density. The luminosity, which is Lorentz invariant, is $E \gamma c/R_e = 1.2 \times 10^{43} E_{46} \gamma^{-2} \gamma_2^2$ erg s$^{-1}$, where $E_\gamma = 10^{46} E_{46}$ erg. In this case the photon energy density in the comoving frame is approximated as $U_\gamma = E_\gamma/(4 \pi R^2 R_e)$. From $B^2/(8 \pi) = \varepsilon_B U_\gamma$, we obtain $B(R) = 1.1 \times 10^{4} \varepsilon_B^{1/2} E_{46}^{1/2} \gamma_2^{-3} (R/R_i)^{-1}$ G, where $\gamma = 100 \gamma_2$. The energy ratio, $\varepsilon_B$, can be larger than unity, if the baryonic energy density is much larger than $U_\gamma$, which implies that the gamma-ray emission is an inefficient process.

The shocks may accelerate non-thermal protons. The maximum energy of accelerated particles, $E_{\text{max}}$, is restricted by the condition that the particle Larmor radius, $r_L = E/\gamma eB$, is smaller than the size scale of the emitting region, $(R - R_i)/\gamma \sim R/\gamma$. This condition gives the maximum energy, $E_{\text{max}} = 8.3 \times 10^{18} \varepsilon_B^{1/2} \gamma_2^{-1} E_{46}^{1/2}$ eV, which is independent of $R$.

Another condition to generate cosmic rays is that the cooling time scale of protons should be longer than the dynamical time scale $T_{\text{dyn}} = R/(c\gamma)$. As long as we consider energies below $E_{L,\text{max}}$, the acceleration time scale ($\sim r_L/c$) may be shorter than $T_{\text{dyn}}$. If the protons accelerated to high energies cool down before they escape from the shell, those particles cannot become cosmic rays. For proton-synchrotron cooling we obtain the maximum energy of $E_{\text{syn, max}} = 4.6 \times 10^{21} \varepsilon_B^{-1/2} E_{46} E_{\text{max}}^{1/2} (R/R_i)$ eV.

We should comment on the “adiabatic cooling” due to shell expansion. While the shell coasts from $R_i$ to $R_e$, the shocked region grows via shock propagation. The adiabatic invariance, $B r_L^2$, may lead to the cooling of particles. However, we are not sure whether the adiabatic condition is satisfied or not for a disturbed magnetic field in the shocked region. In any case, we assume that particles escape from the shell on the dynamical timescale at each radius via stochastic processes. Therefore, we neglect adiabatic cooling in our case.

The maximum energy of cosmic rays is determined by $\min(E_{L,\text{max}}, E_{\text{syn, max}})$. The results are plotted in figure 1. For a smaller $R$ the maximum energy is determined by $E_{\text{syn, max}}$, because the magnetic field becomes stronger. As $R$ increases the maximum energy is determined by $E_{L,\text{max}}$, rather than $E_{\text{syn, max}}$, because the weaker magnetic field cannot confine high-energy particles in the shell. For $\gamma \lesssim 30$ the radius where the shock occurs ($\propto \gamma^2$) is smaller, so that the energy limit is determined by $E_{\text{syn, max}}$ only between $R_i$ and $R_e$. On the other hand, for $\gamma \gtrsim 40$, the limit is determined by only $E_{L,\text{max}}$. The values, $E_{\text{max}}$, achieved in shocked shells
with $\gamma$ are the maximum values in each line in figure 1. For $\varepsilon_B = 1$ and $E_{46} = 1$, $E_{\text{max}}$ may be a few times $10^{19}$ eV.

Fig. 1. Maximum energy, $E_{\text{max}}$, determined by $E_{\text{L, max}}$ and $E_{\text{syn, max}}$ for $\varepsilon_B = 1$ and $E_{46} = 1$. The Lorentz factor, $\gamma$, is assumed to be (a) 10, (b) 25, (c) 30, (d) 40, (e) 100, and (f) 200.

Another cooling process that we should take into account is photopion creation. If the proton photopion “optical depth” is much higher than unity, protons lose their energies in the flare source before they escape from the emitting region (Asano, Takahara 2003; Asano 2005). The condition to create pions is $E_{\text{CR}} \varepsilon_\gamma \geq 0.2 \text{ GeV}^2$, where $E_{\text{CR}}$ and $\varepsilon_\gamma$ are the energies of a nucleon and an interacting photon, respectively. In order to estimate the energy loss rate due to photopion creation, we need the soft photon spectrum in the flare, which is unknown.

If the giant flare is thermal emission of $\sim 200$ keV, the number of soft photons that interact with protons of $\sim 10^{19}$ eV is too small to create pions on the dynamical time scale. However, it may be premature to conclude that the spectrum observed by RHESSI is thermal. As suggested in Mazets et al. (2005) and Palmer et al. (2005), there is a possibility that soft photons due to non-thermal electrons may distribute below $\sim 200$ keV with the spectrum $n(\varepsilon_\gamma) \propto \varepsilon_\gamma^{-p}$, as observed in standard GRBs.

As the most pessimistic case, we assume that power-law photons with $p = 1$ or 1.5 dominate below 200 keV without the low-energy cut-off. Above 200 keV we adopt the Planck spectrum with 200 keV, though the spectrum shape above 200 keV is not important for the cooling process of ultra-high-energy particles. Although the number of power-law photons is much larger than the high-energy photons, the energy contribution of the soft photons is not important for $p < 2$. Using the same cross section and method as Asano (2005), we estimate the time scale of the photopion creation, $T_{\pi i}$ near $R_{\text{max}}$. The results are plotted in figure 2.

The low-energy bump appearing in figure 2. is due to the “thermal” photons above 200 keV. Above this energy nucleons interact with the power-law photons. In this case the number of interacting photons $(n(\varepsilon_\gamma) d\varepsilon_\gamma, \varepsilon_\gamma \sim 0.2 \gamma^2 \text{GeV}^2/E_{\text{CR}})$ is independent of $E_{\text{CR}}$ for $p = 1$. As a result, the time scale is nearly constant in this energy region. For $p = 1.5$ the time scale becomes shorter as $E_{\text{CR}}$ increases ($T_{\pi i} \propto E_{\text{CR}}^{-1/2}$). If the power-law spectrum has a low-energy cut-off due
Fig. 2. Time scale ratio $T_{\text{dyn}}/T_{\pi}$ vs. energy of nucleons for photon index $p = 1$ (solid) and $p = 1.5$ (dashed). The model parameters $(\gamma, R/R_i)$ are (a) $(10, 10)$, (b) $(25, 10)$, (c) $(40, 1)$, and (d) $(100, 1)$. The total photon energy, $E_\gamma$, is fixed as $10^{46}$ erg. The dashed lines of (b) and (c) nearly overlap.

to synchrotron self-absorption etc., the time scale will increase from the corresponding energy.

For $\gamma = 10$ the photopion production is crucial, and resultant high-energy neutrinos will be emitted as is the case in Ioka et al. (2005). However, if $\gamma$ is large enough to generate UHECRs, the photopion production is inefficient. Even for $\gamma = 25$, UHECRs will survive and neutrinos may not be observed, unless the photon spectra are extremely soft, such as $p = 1.5$. Unless the energy of soft photons below 50 keV is much larger than the observed energy by RHESSI, there is a possibility that UHECRs of $> 10^{19}$ eV would come from the SGR 1806–20 giant flare. At present, considering the ambiguity in the parameter values, we cannot completely preclude the detection possibility of UHECRs above $10^{20}$ eV (for example, $\varepsilon_B = 10$, $\gamma = 30$, and $E_{46} = 3$).

3. Propagation of UHECRs

The source location of the flare is about $10^9$ from the galactic center. In the region around the galactic center the magnetic field is highly uncertain. If the magnetic fields are well represented by regular fields along the spiral arms, the time delay may be on the order of $\sim 10$ yrs, even for $10^{20}$ eV (Alvarez-Muñiz et al. 2002). Turbulent magnetic fields, whose scale is $10–100$ pc (Beck 2001), may shorten the above estimate. In the most pessimistic case, the time delay becomes on the order of thousands of yrs (Eichler 2005).

If the energy of cosmic rays above $10^{19}$ eV is $P_{19}$ % of the total photon energy $E_\gamma \sim 10^{46}$ erg, $2P_{19} d_{15}^{-2} \Delta T_3^{-1}$ particles are detected per one year by $1000$ km$^2$ detectors, such as AUGER or Telescope Array, where $\Delta T_3$ is the dispersion of the timedelay normalized by $1000$ yr. If the particles are confined to 0.1 rad of the galactic plane, the above detection rate can be sufficient signals, even for $\Delta T_3 = 1$ (Eichler 2005).
4. Conclusions and Discussion

If the giant flare from SGR 1806−20 on 2004 December 27 is due to internal shocks in relativistic jets, we found that the shocks may produce UHECRs of up to $\sim 10^{19}$ eV. The maximum energy is similar to an estimate by Eichler (2005). In standard GRBs, on the other hand, UHECRs are unlikely to be observed, since they lose energy before escaping from the shell via photopion production (Asano 2005). Even if UHECRs are produced in GRBs, the time delay between cosmological bursts and UHECRs is too large to establish any connection between the GRBs and UHECRs. On the other hand, because the giant flare of SGRs is less luminous than standard GRBs, UHECRs can escape from the shell without losing their energy.

In our baryon-loaded jet model, if the bulk Lorentz factor of the outflow is high enough, neutrinos that are produced from the decay of charged pions may not come from this flare. This is consistent with the results of Ioka et al. (2005). On the other hand, if the outflow is non-relativistic, neutrinos could be produced via p-p collisions, which is neglected in our calculation, in addition to photopion production. Hence, UHECRs and high-energy neutrino observations become diagnostic tools to investigate the properties of the outflows at an early phase. There are three possible cases: A) detection of neutrinos, B) detection of UHECRs, but no neutrinos, and C) no detection of high-energy particles. We may reach the following conclusion irrelevant of the models. Cases A and B mean there are baryons in the flare stage, but the Lorentz factor is not very large in case A (see also Gelfand et al. 2005). Case C implies that there are negligible baryons (pure radiation-pair fireball model), or the UHECR production efficiency is low.

Because the arrival time of UHECRs depends on a number of factors, it cannot be predicted exactly. It might be at present that we will detect UHECRs coming from the other two SGRs (SGR 0526−66, SGR 1900−14) that previously caused giant flares. Giant flares of SGRs could produce a large amount of UHECRs, which may explain the origin of doublet and/or triplet events, though there is no evidence of any correlation between such events observed by AGASA and SGRs so far. Anomalous X-ray pulsars (AXPs) may be the same kind of objects as SGRs and older, but less active than SGRs (Kulkarni et al. 2003). They might have produced UHECRs via giant flares thousands of years ago. We could detect signals from past activities of AXPs by UHECR observations.

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