It is shown that bulk acceleration during reconnection of extremely strong magnetic fields near compact objects can accelerate ions to Lorentz factors of $\sim 10^2 \sigma^{3/5}$ under general conditions, where $\sigma$, the magnetic energy per current-carrying proton rest energy, can approach $10^{15}$. For magnetar-type fields, neutrons and neutrinos can be generated at potentially detectable levels via hadron polarization. Ultrahigh energy photons can also be emitted and escorted from the high field region by Poynting flux.
INTRODUCTION

Magnetic flares on the surfaces of strongly magnetized neutron stars (magnetars) are believed to be responsible for repeating soft gamma ray bursts (SGR events) [1]. While such events are detected primarily in soft $\gamma$-rays, there could be much more energetic quanta produced as well, and there could be more classes of events than those that observations have heretofore identified. Perhaps such events cause other sub-classes of gamma ray bursts as well. As is the case for solar flares and related transient coronal heating phenomena, some magnetar outbursts might be dominated by emission from magnetically trapped plasma, while others might direct most of their energy outward in the form of Poynting flux, and could be much quieter in low energy $\gamma$-rays. Moreover, while some flares may occur on the surfaces of established magnetars, others might occur when a strongly magnetized compact object (SMCO) collapses to a black hole, which, by the no-hair theorem, must swallow or otherwise rid itself of its large scale magnetic field.

This letter suggests that ultrahigh-energy quanta such as cosmic rays, neutrons, neutrinos and photons could all be created in such events at detectable levels, and might even be a common feature to the various types of imaginable events. The primary acceleration mechanism analyzed here, particularly appropriate to SMCO magnetospheres, is bulk acceleration of plasma during magnetic reconnection in the magnetospheres of extremely magnetized compact objects such as SGR’s. It parallels solar flares and magnetospheric substorms in the Earth’s magnetotail, but transplants the mechanism to SGR’s and other SMCO’s, whose huge magnetic fields, $B \gg 10^{14}$ G, combined with huge gravitational fields, create favorable conditions for attaining ultrahigh energies. The mechanism faces no injection problem, because all the particles are accelerated to ultrahigh energies. Pair creation need not short out the electric field, which is perpendicular to $B$, and the pairs do not significantly affect the maximum attainable ion energy as long as their mass density in the zero electric field frame is less than that of the baryons. The key is the rarefaction of the magnetospheric plasma, which is accomplished by the strong gravitational field of the compact object (somewhat analogous to the rarefaction in the Earth’s magnetotail).

A key feature of this acceleration mechanism is its ability to escort high energy quanta: Because the bulk Lorentz factors are so huge, the magnetic field in the zero electric field frame is greatly reduced relative to the static magnetospheric value. Moreover, the energy of emerging high energy quanta is much smaller in the fluid frame than in the lab frame. Thus, high energy photons that would pair produce (and high energy charged particles which would synchrotron cool or curvature radiate) in the strong static magnetic field of the SMCO can be escorted through it by a high Lorentz factor flow.

Consider a strongly magnetized compact object (SMCO, e.g. neutron star, collapsar, steadily accreting black hole) of radius $R$ with a field strength $B$ expressed as $B=\epsilon B^*$ where $B^*$, the maximum field strength imaginable for an object of mass $M$ and associated Schwarzschild radius $R_s = 2GM/c^2$, is given by $B^* = R_s^2/8\pi = Mc^2$. Because the gravitational field allows a negligible thermal scale height, the plasma density well above the surface is determined purely by electrodynamics, and is of order $B/4\pi R\beta$, where $\beta c$ is the velocity of the charge carriers. The characteristic current associated with the field is of order $cB/4\pi R$, and the minimum proton or electron number density associated with this charge density, $n = j/e\beta c$, is $n \sim B/4\pi Re\beta c = 2 \times 10^{17}B_{15}R_6/\beta$ cm$^{-3}$ where numerical subscripts of any quantity refer to powers of ten by which the quantity is to be multiplied when expressed in cgs units. If the current is carried by protons, then the energy per current carrying proton, $B^2/8\pi n$, is of the order of

$$\sigma m_p c^2 \equiv eBR = (4\pi)^{1/2}\epsilon^2 \left(\epsilon Gm_p^2\right)^{1/2} (R/R_s)m_p c^2 \equiv \epsilon^2(R/R_s)\sigma^* m_p c^2$$

(1)
whence

\[ \sigma = 5 \times 10^{18} \epsilon \beta (R/R_s). \]  \hspace{1cm} (2)

While the quantity \( \epsilon \) is sure to be small, it can be as high as \( 10^{-5} \) for magnetars, and the quantity \( \epsilon (R/R_s) \) as high as \( 0.3 \times 10^{-4} \). The energy per current carrying proton can be as high as \( 10^{14.5} m_p c^2 \). If a "failed" or spinning down magnetar collapses to a black hole, then just prior to completing this collapse, it would have a field of about an order of magnitude higher, and \( \epsilon (R/R_s) \sim 10^{-4}; \sigma \sim 10^{15} \).

In practice, a single species plasma would result in extremely high electric fields and the plasma is likely to be quasi-neutral. In this case, the multiplicity \( \xi \), i.e. the ratio of the actual plasma mass density to the minimum needed to provide the curl of \( B \), is likely to be m greater than unity. In pulsars, the charge multiplicity is unknown, but could be as high as \( 10^4 \) or more [2], and if, as will be assumed here, the current carriers include ions, the mass multiplicity is even less certain.

If a significant fraction of the magnetic energy density is stored in a solenoidal component of this field, it could be released by reconnection and current dissipation.

The total magnetic energy of a magnetar can approach \( 10^{47} \) ergs. A SMCO that collapsed through the magnetar stage could undergo a further factor of 30 increase in total field energy. If such objects formed every \( 10^3 \) years or so per galaxy, they could produce up to about \( 10^{44} \) ergs/yr-Mpc\(^3\) in ultrahigh energy cosmic rays, a considerable fraction of the total. This is motivation to consider the maximum energy in greater detail, as done below.

**BULK ACCELERATION**

A sudden eruption resulting from magnetic energy release in a high \( \sigma \) magnetic configuration probably results in bulk motion with a Lorentz factor \( \Gamma \) of order the magnetosonic Lorentz factor \( (\sigma \xi)^{1/2} \). It may be a slow mode shock propagating away from a reconnection point [3, 4], or a sudden decompression of twisted magnetic field lines. The zero electric field (ZEF) in this picture is established by a "piston" of plasma ejected from a magnetic reconnection site. Material swept up just ahead of the piston has about the same Lorentz factor to the piston itself. Bulk acceleration of plasma by a relativistic outflow has been considered by Michel (1984) [5], who finds that the maximum energy attained by a given particle is of order the initial energy times \( \sigma^{2/3} \). Here, since the geometry is likely to be messy, we adopt a simplified but general approach, and generalize Michel’s basic conclusion, more or less, to other geometries.

To simplify geometric considerations, consider a uniform magnetic field \( \mathbf{B} = 10^{15} B_{15} \mathbf{b} \), where \( \mathbf{b} \) is the unit vector in the field direction, and a frame that moves perpendicular to \( \mathbf{B} \) with Lorentz factor \( \Gamma \) relative to the frame of the compact object, hereafter called the lab frame. In the ZEF frame, the field is \( B' = B/\Gamma \) and the Lorentz factor of the particle is denoted by \( \gamma' \).

*Adiabaticity:* The proton gyrofrequency in the ZEF frame is

\[ \omega'_g = eB'/\gamma'mc = 1 \times 10^{19} B'_{15} s^{-1}/\gamma'. \]  \hspace{1cm} (3)

The characteristic proper acceleration time \( \tau'_{acc} \) of the ZEF frame to a Lorentz factor of \( \Gamma \), from a comparable but lower value, is at most the hydrodynamic proper timescale \( R/\Gamma c \), i.e.

\[ \tau'_{acc} \leq R/c \Gamma. \]  \hspace{1cm} (4)

The condition that protons drift with the ZEF is \( \omega'_g \tau'_{acc} \gg 1 \), i.e.

\[ \Gamma^2 \gamma' \leq \sigma. \]  \hspace{1cm} (5)
So for $\Gamma \gamma'^{1/2} \leq (10^{14.5} B_{15} R_6 / c)^{1/2}$, the protons should respond adiabatically to the electromagnetic impulse, and drift in the zero electric field frame. Thus, if large amplitude magnetosonic motion is generated at the Lorentz factor $(\xi \eta)^{1/2}$, the individual Lorentz factors of the typical plasma ions may be comparable. (Note that if a particle at rest in the lab frame is suddenly picked up, then $\gamma' = \Gamma$, and the maximum attainable lab frame energy is $\sigma^{2/3}$, similar to the result obtained by Michel [5] for the specific case of stationary radial winds.)

Particles that begin with large Lorentz factors $\gamma_i$ in the lab frame, $\gamma_i \gg 1$, can ultimately achieve energies even greater than $\sigma^{2/3} m c^2$ if $\Gamma$ remains below $\sigma^{1/3}$. Ultra-relativistic MHD turbulence where independent cells attained Lorentz factors of $\Gamma$ could accelerate ions via multiple encounters to

$$\gamma_{\text{max}} = 2 \gamma'_{\text{max}} = 2 \sigma / \Gamma.$$  (6)

Though analogous to second order Fermi acceleration, such a process would be nearly as efficient as a first order process because the changes in energy are in large increments.

The synchrotron loss time for a charged particle of mass $m$ is given by

$$\tau_{\text{syn}}^{-1} = \gamma' e^4 B'^2 / 3 m^3 c^5 = \gamma' e^4 B^2 / 3 m^3 c^5 \Gamma^2.$$  (7)

The condition that $\tau_{\text{syn}}' \geq R / \Gamma c$ can be written as

$$\gamma' \leq \gamma'_{\text{cool}} \equiv 3 \Gamma^3 c / \sigma r_o \omega_g \leq 1$$  (8)

where $r_o$ is the classical electromagnetic radius of the particle. Writing the maximum lab frame energy as $2\gamma' \Gamma = 2(\gamma' / \Gamma^{3/5})(\Gamma^{2/5} \gamma')^{1/5}$ and using equations (5) and (8), one concludes that synchrotron losses are small provided that

$$2 \gamma' \Gamma \leq 70 \sigma^{3/5} (m / m_p)^{2/5} B_{15}^{-1/5}.$$  (9)

We conclude that near SMCO’s, protons can attain Lorentz factors of nearly $\sim 10^{11}$ by this mechanism.

**MESON PRODUCTION**

**Polarization Induced Mesons:** If a hadron propagates with a Lorentz factor $\gamma'$ relative to the zero electric field frame, then there is an electric field of $\gamma' B'$ in the rest frame of the hadron. When this field exceeds $\frac{2}{9} T / e \left[ \frac{3}{4} T / e \right]$, where $T$ is the QCD string tension $1 \times m_p^2 c^3 / \hbar$ ($0.16 GeV^2$ in units where $\hbar = c = 1$), a proton [neutron] is electrically polarized enough to overcome QCD confinement and the hadron is stretched into a long flux tube over a timescale of $10^{-23}$ s. Virtual quark pairs will materialize along this color flux tube, and probably the negative and positive quarks are each pulled to opposite sides. We therefore conjecture that the resulting pions are mostly charged and ultimately decay into neutrinos. The mechanism operates even at constant velocity, and even on neutrons, but is otherwise reminiscent of curvature pion radiation [11].

This threshold occurs at a Lorentz factor (still in the zero electric field frame) of

$$\gamma'_{\text{th}} \sim m_p^2 c^3 / \hbar e B' \perp \Gamma_{15} B'_{15}^{-1}.$$  (10)

Any hadron that is injected at $\gamma' \geq \gamma'_{\text{th}}$ generates additional mesons. Because the proper time is much less than the decay time of a pion, pions reproduce themselves as long as their Lorentz factor in the zero electric field frame exceeds $\gamma'_{\text{th}}$. 
A hadron could establish sufficient cross-field motion to exceed the threshold $\gamma_{\text{th}}'$ established by equation (10) via inertial forces while following curved field lines. Also, a UHE neutron, once produced (by photopion production, say), could coast into some other cell of ultrarelativistic turbulence where its local Lorentz factor could exceed $\gamma_{\text{th}}'$.

For simplicity, consider an ion that has already been accelerated to UHE energies that is now exiting the acceleration region along static curved field lines, so that that the ZEF frame is (only in the present example) the lab frame. Ions that move with Lorentz factor $\gamma_\parallel$ along curved magnetic field lines with a radius of curvature $R_c$ experience a perpendicular acceleration of $a_\perp = c^2/R_c$. In the frame of the ion, where the perpendicular acceleration $a'_\perp$ is $a'_\perp = \gamma_\parallel^2 a_\perp$, the force is $F' = \gamma_\parallel^2 m_i c^2/R_c$.

The differential electromagnetic force on a proton is $5/3$ of the total force, and when this exceeds the tension in the color flux tubes that bind oppositely charged quarks, the hadron emits a steady steam of mesons until it has slowed down to below the threshold for this process. Thus for

$$\gamma_\parallel \geq \gamma_{c,\text{th}} \equiv (R/r_p)^{1/2} = 2 \times 10^6 R_6^{1/2},$$

(11)

where $r_p$ is the radius of the proton, one Fermi, pions would be emitted, so the Lorentz factor of parallel motion is limited to this in the zero electric field frame. By equation (7) above, this threshold Lorentz factor for polarization-induced pion production can be achieved for $R_{\text{ed}} B_{15} \sim 1$. For protons, however, electromagnetic curvature radiation would limit the Lorentz factor to $(R_c m_p c^2/e^2)^{1/3}$, which is below the above limit.

It is easier, on the other hand, for neutrons to establish enough cross-field motion to meet the threshold condition (10). Even a $\pi^0$, moving at a $\gamma$ of $10^{10} \gamma_{10}$, travels $\sim 2 \times 10^4 \gamma_{10} \text{ cm}$ before decaying. Over this distance, the field would curve by $2 \times 10^{-2} R_6$ radians, and this is enough to cause the $\pi^0$ to further cascade. Thus, neutral hadrons with $\gamma \geq \gamma_{c,\text{th}}$ loosely follow field lines. It can be shown that they lose about $\delta \theta$ of their original energy to meson production as the field curves through an angle $\delta \theta$. Neutrons with $\gamma \geq \gamma_{c,\text{th}}$ could thus escape the system along moderately polar field lines without losing most of their energy to mesons, though they might lose of order half or so.

**Photopions and Neutrons:** Any neutron stars that emit X-rays at $\eta L_{\text{edd}}$ where $L_{\text{edd}}$ is the Eddington luminosity can convert protons to neutrons and accompanying $\pi^+$'s within about $\eta 10^{8.5} \text{ cm}$ [12]. Magnetars, which emit steadily at about $10^{-3} L_{\text{edd}}$, can thus convert over $10^{-1}$ of UHE protons above $10^{14.5} \text{ eV}$ produced near their surface. The fraction can be higher if the protons undergo many ultrarelativistic oscillations while trapped on a field line, and when the X-ray luminosity goes up during the flare.

Magnetars also emit optical and near IR radiation [13, 14, 15]. If due to coherent plasma instabilities in the magnetospheric currents [16], this should be a generic feature of magnetars, although in most cases such emission would be obscured by interstellar dust. Corrected for reddening, the intrinsic optical luminosity of the magnetar 4U0412 is probably about $10^{33}$ erg/s. These photons, energy of order 1 to 2 eV, may be generated by coherent processes near the magnetar surface, and their density is of order

$$n_\gamma = 10^{21} \text{ cm}^{-3} L_{33} R_6^{-2}.$$  

(12)

The cross section for photopion production above the threshold $300 \text{ MeV}$ in the frame of the proton is $3 \times 10^{-28} \text{ cm}^2$. The optical depth to photopionization by optical photons over a length of $10^6 R_6 \text{ cm}$ is thus above $10^{-1}$ per passage, and neutrons can be formed in significant quantities by optical photons from protons with lab frame Lorentz factors of order $10^{8.5}$. Iron nuclei would be photodisintegrated at Lorentz factors about $10^4$ ($10^7$) by X-ray photons (optical photons), and this is another way to produce free neutrons at $\Gamma \geq 10^4$ ($\Gamma \geq 10^7$).
PHOTON PICKUP

A photon with lab frame energy \( E_{ph} \) has an energy in the frame of the piston of \( \Gamma E_{ph} \) to within a geometric factor. Photons with lab frame energy above \( (B_{QED}/B)m_e c^2 \) pair produce in the ZEF frame. The pairs emit synchrotron radiation at a frequency of \( 2 \times 10^7 \gamma'^2 B'_0 \) where \( B'_0 \) is the ZEF field strength in Gauss. As they slow down, they emit an increasing number of photons per decrease in \( \ln \gamma' \). Assuming a classical approximation

\[
d\gamma'/dt' = \gamma'^2 \sigma_T B'^2 / 8 \pi m_e c
\]

(13)

\[
d\theta/dt = eB'/\gamma' m_e c,
\]

(14)

it is straightforward to show that the photons emitted after 1/4 of a gyroperiod (\( \theta = \pi/2 \), i.e. perpendicular to the fluid velocity) are emitted in the ZEF frame at an energy \( \epsilon' \) of

\[
\epsilon' = \hbar \gamma'^2 eB'/mc = 3m_e c^2/\alpha \pi.20
\]

(15)

The energy is the lab frame is thus

\[
\epsilon = 67\Gamma MeV
\]

(16)

which, for the magnetosonic value of \( \Gamma, \Gamma = (\sigma/\xi)^{1/2} \), can exceed \( 10^{15}(\sigma_{15}/\xi)^{1/2} \) eV. Photons this energetic could not escape from static SMCO magnetospheres. However, they survive in the high \( \Gamma \) outflow, which has a much lower field than the lab frame. If the ZEF frame is outward going, the Poynting flux escorts the high energy photon out to large distances. A photon with the energy \( \epsilon' \) given by equation (15) is below the pair production threshold as long as \( B' \leq \pi \alpha B_{QED} \). The final lab frame energy depends only on the Lorentz factor of the fluid element that finally escorts it to a region where the static field is too weak for pair production.

The number of second generation photons emitted per first generation photon is of order \( B/B_{QED} \). This could be somewhat less than unity for solar mass SMCO’s, suggesting that a quantum calculation is called for.

DISCUSSION

An actual flare from a magnetar or other SMCO may be quite complicated, because the photon flux increases by many orders of magnitude during the event, because the Lorentz factor of the ultrarelativistic turbulence is likely to vary widely, and because the flare itself would distort the preexisting magnetosphere in ways that are hard to predict. As such, the preceding discussion has been deliberately general. Using the considerations of previous sections, we can suggest a sample scenario using parameters at the beginning of the flare keeping in mind the uncertainties: Magnetic reconnection leads to a large scale motion of field lines. The Lorentz factor \( \Gamma_1 \) is as much as \( (\sigma/\xi)^{1/2} = 10^{7.5}(\sigma_{15}/\xi)^{1/2} \). This is enough that protons dragged by the field lines are photconverted to neutrons which then pass freely to regions where the ZEF magnetic field is of order \( 10^{15}/\Gamma_2 G \). There they emit mesons until decelerating to the threshold \( \gamma'^{th} = 10^4.5 B_1^{-1} \Gamma_2 \) defined by equation (10). In doing so, they can convert back to protons. If \( \gamma'^{th} \leq \sigma/\Gamma_2^2 \), as per condition (5), they may reverse direction in the ZEF frame and cool down to \( \gamma'^{cool} \). The final lab frame Lorentz factor after this reversal is then given by the right hand side of equation (9), and, if the energetic protons eventually attain isotropy in the fluid frame, they have a flat energy distribution out to this maximum value in the lab frame. (If, on the other hand, the reconstituted proton does not satisfy
equation (5), it passes through that cell of turbulence or synchrotron breaks until it has slowed enough in the second fluid frame to do so, or else escapes the system.

Alternatively, though for a more specialized geometry, we could suppose that protons pass through a slow shock [3], the Petschek model of magnetic field line reconnection, in which magnetic energy is converted to particle kinetic energy. Downstream of the shock, the fluid moves in the plane of the shock with bulk Lorentz factor $\Gamma$. Although we have no rigorous theory of collisionless slow mode shock structure (much less in the ultrarelativistic limit) we assume that the ions are picked up suddenly (i.e. $\gamma' = \Gamma$) subject to the constraint of equation (5) and conjecture that $\Gamma \sim \sigma^{1/3}$ and that the particles attain lab frame energies of up to $\sigma^{2/3}$. Note that equation (5) expresses a necessary condition for the validity of MHD, whereas reference [3] assumes MHD. Thus, the former can be more restrictive in high $\sigma$ environments. It expresses the restriction that the shock thickness cannot exceed the dimensions of the region.

Either of the above variations allows final Lorentz factors in the lab frame well above $10^9$, and the proton could reconvert to a neutron upon exiting the region. There is thus some chance that neutrons so produced could arrive intact at Earth from a distance of 10 Kpc.

Given a number density of current carrying protons of $10^{18} B_{15}/R_6$ over typical dimensions of $10^6$ cm, the number of available protons could be of order $10^{35}$ or more. (Note that if the burst lasts more than a dynamical timescale, the current carriers turn over, and the time integrated total can be more than at a given instant.) If a significant fraction of them are neutronized at Lorentz factors $\Gamma$ above $10^9$, then they propagate 10 Kpc before decaying. At a distance of 10 Kpc, a burst of $10^{44}$ ergs that puts $10^{-4}$ of its energy into $10^{34}$ neutrons at $\Gamma = 10^9$ creates a fluence of $10^{-2}/km^2$. A collecting area exceeding $100 km^2$ might have had some chance of detecting UHE neutrons from the Aug. 27, 1998 flare. Similarly, a $10^3 km^2$ array might have had the chance from the April 18, 2001 flare, which emitted about $10^{43}$ ergs.

The charged pions emitted typically cool until they marginally satisfy equation (8) suitably adapted to pions, i.e. until $\gamma' = 3\Gamma^3 c/r_{\pi,o}\sigma\omega_{\pi,g} \sim 1.3 \times 10^7 \Gamma^3 / \sigma$, and they can produce extremely energetic neutrinos, of order $E_\nu = \gamma'm_\pi c^2 / 4 \sim (5 \times 10^{14} \Gamma^3 / \sigma) eV$. The neutrino fluence at Earth that would have resulted from the Aug. 27 flare would have been $10^{-2}$ erg/cm$^2$ if all the observed flare energy had gone into neutrinos. Several percent of this in the range $1 TeV \leq E_\nu \leq 10^3$ TeV is detectable with 1 km$^3$ detectors.

A photon fluence of $10^{-2}$ erg/cm$^2$, the energy equivalent of the soft $\gamma$-rays from the Aug. 27 giant flare from 1900+14, would produce a huge signal in MILAGRO if the photon energies exceed 1 TeV. If energies approach that given by equation (16) with $\xi = 1$, then the maximum energy can exceed $10^{15}$ eV and this should be accessible with air shower detection.

As the flare from a magnetar progresses, and the photon luminosity increases, the emission from a vibrating magnetosphere should be increasingly dominated by the emission of pairs from swept-up photons. However, this is not necessarily true if the energy is released in outward Poynting flux or if a black hole forms during the collapse of a SMCO; in these cases there may be little thermalization of UHE emission.

Altogether, ultrahigh energy emission could be a major component of the radiative output of giant flares on SMCO’s. If it could carry most of this output, it could conceivably allow magnetospheric rearrangement that is quiet in soft and medium energy $\gamma$-rays, which is suggested by the sudden changes in the spin down rate observed for some magnetars. However, this possibility requires further investigation.

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