Ultrahigh Energy Activity in Giant Magnetar Outbursts

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October 25, 2018

Abstract

The recent superflare of 27 December 2004 from the magnetar SGR 1806-20 was the brightest extrasolar flash ever recorded in the modern era. The chances for seeing exotic ultrahigh energy (UHE) radiation - neutrons, neutrinos, gamma rays and charged cosmic rays - from it are far better from an energetic point of view than from cosmological gamma ray bursts (GRBs). The chances for detecting the various components are discussed in light of recent data from the 27 December event.

1 Introduction

Giant flares from magnetars - most recently observed from SGR1900+14 on 27 August 1998 and from SGR1806-20 on 27 December 2004 - were considered as a source of high energetic neutral particles: neutrons, neutrinos, and photons (Eichler 2003, 2004, Gelfand et al. 2005, Ioka et al. 2005, Halzen et al. 2005).Until recently, their low occurrence rate in the galaxy, once every 20 years or so, rendered the subject as being of no obvious urgency. Moreover, the fluxes of neutrons and neutrinos were scant enough for the 27 August flux levels that a positive signal might have been expected only very rarely. Much larger flares ($\geq 10^{46}$ ergs) were also considered in Eichler (2002) but the expected occurrence rate in our galaxy, given the limits imposed by the

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rate of short gamma ray bursts (GRBs), suggested that the event rate per galaxy was at most one in several hundred years. This estimate can be made without reference to extragalactic data by assuming a dozen magnetars per galaxy and that each one has an active phase lasting 3,000 to 10,000 years. At present, the distance to which the December 27th flare could have been seen has been estimated to be $50d_{15Kpc}$ Mpc (Palmer et al. 2005). Here, $15d_{15Kpc}$ Kpc is the actual distance to SGR 1806-20 (Corbel and Eikenberry 2004). This estimate, assuming a distance of 15 Kpc, suggests that the 27 December flare could have be seen in the 30,000 closest galaxies or so. The upper limit on detection of such events is currently estimated to be about 50 per year (Gehrels, private communication) so the upper limit on the event rate per galaxy is approximately one per 600 years, with obvious uncertainties due to small number statistics. The odds of it happening once in 40 years per galaxy are thus small, though not implausibly so.

The recent supergiant flare of 27 December 2004, which came as a surprise, can be attributed to luck. It may be that our galaxy is somewhat atypical so that the a priori odds of its happening once in a human lifetime are not implausibly small; for example, not many galaxies the size of ours have recently collided with a galaxy as large as the Magellenic Clouds and the magnetar production rate in our galaxy could plausibly be a factor of several times higher than in the average galaxy. Magnetar production per unit mass in our galaxy and in the Magellenic Clouds could be somewhat higher than average. This fact could prove to be important in considering giant flares as a source of UHE cosmic rays, which require an output of about 10^{44} ergs per year (in UHE cosmic rays) per average large galaxy.

In any event, the 27 December event, however improbable it may have been, has nevertheless occurred and has refocused attention on the issue of ultrahigh energy neutrals (Gelfand et al. 2005). Because it was 100 times brighter than the next brightest event, that of 27 August 1998, the fluxes that are worth considering could have been quite detectable with existing underice neutrino detectors (AMANDA) and airshower arrays. Since the event has already happened, either these fluxes were detected or they weren't. The purpose of this letter is to provide the experimentalist with a general guideline of what might be expected. We briefly review the prospects for ultrahigh energy neutrons, neutrinos, photons, and charged cosmic rays, in light of the data for the 27 December event that have been reported thus far.

Neutrons can be detected only at a Lorentz factor $\geq 10^9$ (Eichler 2003), or else they would not cross the galaxy before decaying. Neutrinos are best detected between energies of 1 and 100 TeV. Photons could have been detected by airshower arrays at energies above 10^{14} eV and by MILAGRO above 10^{12} eV. Charged cosmic rays can be seen only over the course of many years as they do not propagate to earth in a straight line.

The immediate questions that arise upon which theorists might be able to provide some guidance are how the energy in the flare might distribute itself among these and other forms of energy, what energy range is predicted, and what time scale is predicted. These depend strongly on whether the flare puts most of its energy into pair plasma, relatively devoid of baryons, and how much goes into baryon-contaminated plasma, and at what Lorentz factor these components are ejected. A second question is the spectrum of ultrahigh energy charged particles that are produced.

Given the basic hypothesis that the flare is due to magnetic reconnection in the magnetosphere, one naively expects that the plasma be highly pair-dominated, because baryons are constrained by gravity not to populate the magnetosphere. However, there may be several reasons to expect baryons: 1) Baryons in some small measure may populate the magnetosphere due to electromagnetic forces, especially if they are mobilized as carriers of the electric currents. Such a population of dilute baryons can none the less absorb significant amounts of energy if they dominate the inertia of the magnetically reconnecting plasma (Eichler 2003), and they would attain particularly dramatic individual energies. 2) Baryons may be dredged up from just below the surface of the magnetar. In a recent paper (Gelfand et al. 2005) it has been shown that more than 10^{24} g of material is present in the radio afterglow nebula and the natural explanation for this is that they were ejected from the magnetar itself. Alternatively, the baryons may have been in the ambient medium but the measured expansion trajectory is difficult to explain unless these baryons were concentrated improbably close to the magnetar (Granot et al. 2005).

The expanding radio nebula has been fit with a baryonic shell of mass greater than 10^{24} g and expansion velocity of about 0.3c, assuming that it is roughly spherical (Gelfand et al. 2005). This does not preclude a more relativistic component, though such a relativistic component would probably be required to store its energy in relativistic baryons in order to avoid annihilation. However, in another paper from this collaboration, Granot et al. (2005) argue that the radio emission that is currently being observed cannot be attributed to relativistic outflow, and this constraint sets a rather high minimum for the amount of rest mass. If the ejecta are one-sided, the inferred expansion velocity is about 0.6c but the opening angle is considerably smaller than 4π, the energy estimates as expressed by Gelfand et al. (2005) are thus insensitive to this matter. There exists the possibility that this mass was actually ambient material, as the magnetar probably lives in a molecular cloud complex. However, the energy transfer from relativistic ejecta to the ambient material is unlikely to be 100 percent efficient in view of Rayleigh-Taylor instabilities and this would only raise the minimum energy requirements on the relativistic ejecta, particularly if the relativistic ejecta in their present state are mostly one-sided. The opacity of matter leaving the magnetar surface increases with distance as the magnetic field decreases and it is not unlikely that a large fraction of the ejected energy, even if originally in the form of radiation, could drive some of the ejected matter to relativistic velocities and end up in that form.

To summarize all of the above, the total flare energy, at least 2×10^{46} ergs can distribute itself in extremely high Lorentz factor plasma, relativistic baryons, and non-relativistic baryons, though it seems that the component in relativistic baryons is energetically the smallest of the three. The present radio nebula was driven by non-relativistic baryons (Gaensler et al. 2005, Gelfand et al. 2005, Granot et al. 2005), so we now have observational evidence for at least this component, as well as the gamma ray component, which almost certainly came from baryon-poor pair plasma.

2 Mass Loss

The fits to the expanding radio nebula suggest a minimum mass ejection of several times 10^{24} g. There are several reasons for believing this mass was ejected during the initial hard spike phase of the giant flare. The tail phase, which lasted several minutes, has a well-defined time structure (on a sub-second time scale) suggesting that the optical depth through which it was observed was small, yet this is unlikely to have been the case if the baryonic outflow had been emitted over many rotation periods (as it would demand a line of sight that was much cleaner than average). If, on the other hand, the matter was ejected during the first 0.5 seconds of the flare along many lines of sight, none of them need have swept across our line of sight during such a small fraction of the rotation period (7.6 s). Although there was apparently more than enough matter in the ejecta to have obscured the observed gamma ray flare if it were present at the source, we suggest that it was emitted extremely anisotropically. Probably, the baryon content of the energy outflow was very strongly dependent on its point of origin and/or time of origin at the magnetar surface. This strong dependence was accomplished without an event horizon and we suggest that it is an intrinsic property of magnetic field annihilation in a highly stratified medium. The extent of mass loading on magnetically-driven outflow can be very sensitive to initial conditions. In a purely one-dimensional situation with the magnetic field perpendicular to the gravitational force, the mass density $\rho(t)$ on any given field line is proportional to $\rho(0)B(t)/B(0)$. In hydrostatic equilibrium

$$\rho g = \rho(0)B/B(0)g = \frac{d}{dz}(B^2/8\pi) = B\frac{d}{dz}(B/4\pi) \qquad (1)$$

Writing g as $\frac{d\Phi}{dz}$, this can be integrated to

$$B(0) - B(z) = 4\pi \int \rho(0)/B(0) d\Phi \qquad (2)$$

Given that, in a realistic geometry, the right hand-side is bounded, the change in field with altitude, depicted by the left-hand side, is also bounded. This shows that depending on the initial mass loading, some field lines will blow off to infinity and others will remain bound to the magnetar. However, in a more realistic geometry, magnetic fields would arch up and matter would fall away from the rising apex of the arch back towards the star and the mass loading near the apex could decrease substantially with time. Thus magnetic fields rising from below the surface could shed their matter if they rose sufficiently gradually. Moreover, much of the reconnection could take place above the surface at an altitude that guaranteed a nearly vanishing baryon density. On the basis of the above considerations, we conclude that the amount of matter dragged out by erupting magnetic field lines is not only hard to predict, but is likely to be highly variable as a function of space and time on the surface. This squares with the naively paradoxical observations that seem to indicate both a large gamma ray flux directly from the surface as well as a mass loss. A similar explanation might be given for the coexistence of prompt gamma rays and after-glow-generating ejecta from cosmological distant gamma ray bursts (GRBs). Note, however, that in the case of cosmological GRB, the duration of the event is much longer than the rotation period of the central powerhouse, whereas in the case of the initial hard spike phase of giant flares from SGRs, the reverse is true. As rapid rotation is likely to blend baryon-rich components and baryon-poor components on any given line of sight, cosmological gamma ray bursts might exploit a systematic polar angle-dependence in the baryon richness such as might be expected from a black hole-accretion disk system (Levinson and Eichler 1993).

3 Particle Acceleration

We now address the question of particle acceleration. We consider both shock acceleration and bulk acceleration following magnetic reconnection.

Particles can be accelerated by internal shocks in relativistic outflows to energies as high as $\sim 10^{21} B_{15}$ eV (e.g., Levinson and Eichler 1993), where B is the magnetic field strength at the base of the flow, here a neutron star. (In this paper numerical subscripts obey the convention $Q_n = 10^{-n} Q$ in cgs units unless otherwise stated.) This estimate was made for an outflow from a rotating neutron star considering the potential drop along open field lines and with due allowance for a reduction in the highest possible energy for internal shocks. Strictly speaking, a flow characterized by magnetic field B velocity βc and transverse radius R can accelerate particles of charge Ze through a maximum energy of

$$E_{max} = \sigma m_p c^2 \equiv ZeBR\beta \tag{3}$$

(Eichler 1981, the so-called Hillas limit). Here m_p is the mass of the proton, Ze is the charge of the particle, and βc is the shock velocity. For an outflow of βc from a neutron star of radius R_{NS}, $\sigma \sim 10^{14.5} \beta B_{15} R_{NS}$. If the source is rapidly rotating so that B decreases as 1/r, then assuming R and r are of the same order, σ remains roughly constant with r. In the case of outflow from a magnetar, however, the flow out to nearly the light cylinder is not strongly effected by rotation and the field lines are probably radial. In this case, B decreases as $1/r^2$ and hence $\sigma(r) \propto 1/r$. At a characteristic radius r of $10^{10} r_{10}$ cm σ is thus $10^{10.5} \beta B_{15}/r_{10}$ and it thus difficult to accelerate protons beyond 10^{20} eV if the flow stretches the magnetic field radially to 10^{10} cm.

The maximum energy is, in any case, limited by ion-synchrotron radiation to

$$E_{max} = 70 \sigma^{\frac{3}{5}} (\frac{m}{m_p})^{\frac{2}{5}} m_p c^2 B_{15}^{-\frac{1}{5}} \tag{4}$$

where m is the mass of the particle (Eichler 2003), so that close to the neutron star it is likewise difficult to accelerate protons beyond 10^{20} eV. Assuming that $B \propto 1/r^2$, it follows that $\sigma \propto 1/r$ and E_{max} decreases with r. So the maximum value to which a proton can be accelerated is $6 \times 10^{19} B_{15}^{\frac{2}{5}} R_{NS,6}^{\frac{3}{5}}$ eV. Heavier ions could attain a higher total energy but would be limited to a lower energy per nucleon, and it is unlikely that they would survive the intense radiation field intact if accelerated close to the surface.

Let us now consider the efficiency with which the highest energy particles can be accelerated. If the shocks are relativistic, models based on small angle scattering predict (Bednarz and Ostrowski 1998, Vietri 2003, Keshet and Waxman 2004) that their spectral index is -p = -2.25. This implies that the energy component in neutrons at $\Gamma \geq 10^9$ is less than 10^{-2} of that in the shock accelerated particles. Large angle scattering in relativistic shocks, on the other hand (Ellison and Double, 2002) gives rise to very hard spectra and eliminates this problem. It is possible, of course, that subrelativistic shocks can be embedded in a highly relativistic outflow. Subrelativistic shocks, if at a high enough Mach number, can, in fact, put most of their energy into particles at the highest energy.

Bulk acceleration following magnetic reconnection is still a somewhat open question. Lyutikov and Uzdenski (2003) conjectured that Lorentz factors as high as σ are attained within the reconnection region. Lyubarsky (2005) constructed a model in which the Lorentz factor of the material ejected from the reconnection region is always below $\sigma^{1/2}$, with the maximum attained only for reconnection of field lines that are anti-parallel. Eichler (2003) made the starting assumption that Γ is of the order of $\sigma^{1/2}$ without proof, and considered the consequences of turbulent ejecta with this typical value for Γ. In ultrarelativistic turbulence, second order Fermi acceleration can be extremely efficient and accelerate particles up to the limits mentioned above. Theoretical steady-state solutions to force-free electrodynamics typically suggest that for asymptotic outflows, the Lorentz factor increases linearly with radius and that the magnetosonic point (where $\Gamma \sim \sigma^{1/2}$ for an extremely high γ outflow) would occur only at very large radii. (The force-free electrodynamic approximation, in any case, breaks down near the fast magnetosonic point, where, by definition, inertia is important.) At very large radii, many of the emission mechanisms discussed in Eichler (2003) would not be relevant. However, it is possible that in time-dependent explosive outflows the Lorentz factor is higher much closer to the surface (Lyubarsky in preparation). Close to the surface, protons easily generate neutrons and neutrinos by photopion reactions (e.g., Eichler 1978). The neutrinos will typically carry 5 to 10 percent of the proton energy and emerging neutrons would contain much or most of the initial proton energy and arrive essentially simultaneously with photons emitted at the same place and time.

Now consider charged UHE cosmic rays. The discussion here presents a less optimistic picture than that of Asano et al. (2005). A particle of charge Ze and energy $10^8 E_8$ in the interstellar medium (where $B \sim 3\mu$G) has a gyroradius r_g of $6 \times 10^{22} E_8 B_{-5.5}$ cm. This is comparable to the distance from us. In traversing $d = 10^{22.5} d_{22.5}$ cm, its traversed distance deviates from that of a straight line connecting its end-points by $2r_g(\theta - sin\theta)$ where $2rsin\theta = d$. To lowest order in θ, this yields $d^3/16r_g^2$. Here we have assumed a constant field. A more detailed model by Alvarez-Muniz, Engel and Stanev (2002) yields a delay of only about $10^2 B_{-5.5}/E_8$ years from a distance of 20 Kpc. This estimate is in any case highly uncertain as our knowledge of the Galactic field is limited. Turbulence can reduce the delay for some particles and increase it for others, but the presence of an underlying large scale field would suggest a minimum delay for most particles. The fluence in UHE cosmic rays would be $1 \times 10^2 \epsilon_{UHE}/E_8$ particles per km^2. Here ϵ_{UHE} is the efficiency with which UHE cosmic rays are produced relative to the burst energy, $2 \times 10^{46} d_{15Kpc}^2$. A liberal estimate for ϵ_{UHE} in any given logarithmic interval of energy is about 10 percent (Ellison and Eichler 1985). A liberal estimate for the enhanced flux of UHE cosmic rays in the energy range of 3×10^{19} - 10^{20} eV from the direction of the Galactic center is thus of order 0.1/km^2-yr. It is worth looking for weak anisotropies in the Galactic disk from previous magnetar outbursts as their event rate in the Galaxy is probably more than one per 1000 years. A flux of even 10^{-2} per km^2-yr at $E_8 \simeq 1$ confined to 0.1 radian of the Galactic plane could be detectible with AUGER, which should detect a total of 100 per year at these energies.

The question of whether giant flares from magnetars could provide all of the UHE cosmic ray background is not much changed by the huge energetics of the 27 December event. A magnetar has of the order of 10^{47} ergs to release, regardless of how this quantity may be divided into individual bursts. In our Galaxy, the production rate of known magnetars appears to be 1 to 3 per 1000 years. This follows directly from the fact that there are 12, including those in the Magellanic Clouds and that their active lifetime, as deduced from their association with supernova remnants, appears to be several thousand years. This suggests that magnetars have barely enough energy to account for the UHE cosmic rays and, given the uncertainties both in the theory and observations, little more can be said at the present time. Whether our

Galaxy is completely typical in its magnetar production rate is also an open question at present. However, observations of extra-galactic magnetar flares, which should be available from Swift (Eichler 2002) should help settle this question.

4 Summary of scenarios for UHE emission

To summarize, it appears to this author that most of the theoretical possibilities that have been, or are likely to be, discussed in the literature are presently possible, and are even supported by observations of the radio nebula. The fraction of energy that is in subrelativistic baryons appears from the radio data to be at least 1 percent of the flare energy, but any energetically plausible higher value is also consistent with the data. It is unlikely that the vast majority of the blast energy is in ultrarelativistic baryons or pairs, as it would have produced a more rapidly expanding nebular shell. However, the amount of energy in such a component may easily be within an order of magnitude or so of that in the subrelativistic baryons (Ramirez-Ruiz, private communication) because it could have been slowed and overtaken by the latter within the first ten days after the explosion. The huge energy emitted in gamma rays is probably even larger than the blast energy and is therefore even less likely to be matched by a comparable component in ultrarelativistic pairs or even ultrarelativistic baryons. However, the present observations of the radio nebula probably admit as much as 10 percent of the flare energy in ultrarelativistic baryonic outflow. The observations imply at least 10^{44} ergs and as much as 10^{46} ergs in modestly relativistic baryons and admit as much as 10 percent of this quantity in ultrarelativistic outflow. The Lorentz factor of such outflow can be anywhere between 1.1 and 10^{14}, and it is quite reasonable to suppose that we will receive a diverse sample from this wide range.

The prompt neutrons, which require $\Gamma \geq 10^9$, could be detected with high statistical significance if they are, in fact, efficiently produced. UHE protons, whose arrival even at the highest conceivable energies would be spread out at least several thousand years, are less likely to be detected with overwhelming statistical significance, but even a fluence of 10^{-2} per km^2-year, comparable to the background flux, would be a statistically significant signal in AUGER given its large area. These particles need not necessarily arise from SGR1806-20; they may arise from other galactic magnetars as well. While we have argued that the maximum energy of protons is unlikely to exceed 10^{20} eV, high energy particles should, nevertheless, be looked for.

Plausible values for the neutrino flux from the 27 December event have been very recently discussed by Gelfand et al. (2005), Ioka et al. (2005), and Halzen et al. (2005). There are large uncertainties in the predicted flux but, given the evidence for baryonic ejection (Gelfand et al., 2005) and the huge total fluence at Earth, this event is arguably the most promising transient source of neutrino to date.

Ultrahigh energy photons are easily produced given particle acceleration, but whether they escape is problematic. Levinson and Eichler (2000) have presented a detailed analytic calculation of escape criteria for UHE cosmic rays. For γ-ray energy spectrum of E^{-2} (most of the spectra give less photon-photon opacity) and a γ-ray energy of $\epsilon_\gamma m_e c^2$, the gammaspheric radius is given by

$$r_\gamma(\epsilon_\gamma) = 2.8 \times 10^{10} \frac{L_{51}}{\Gamma_2^4} \epsilon_\gamma \text{ cm} \tag{5}$$

where L is the γ-ray luminosity. During the initial hard spike of the 27 December flare, which lasted $\delta t \sim 0.3$ s, $L_{51} \sim 10^{-4}$. Photons more energetic than 10^{14} eV have $\epsilon_\gamma \geq 2 \times 10^8$, so in order for them to escape from within $\Gamma^2 c\delta t$ of the source, the Lorentz factor of the outflow, Γ would have to exceed 10^2, and this threshold is only weakly dependent on ϵ_γ. This is achievable by magnetic reconnection in baryon-poor regions of the magnetosphere, where bulk motions with Lorentz factors as high as $\sigma^{1/2}$ are in principle possible at the reconnection site (Eichler 2003, Lyubarsky 2005) and perhaps as high as σ in the post reconnection flow (Lyutikov and Uzdenski 2003).

I thank Drs. B. Gaensler, N. Gehrels, Y. Gelfand, J. Granot, C. Kouveliotou, Y. Lyubarsky, E. N. Parker, E. Ramirez-Ruiz, and P. Woods for useful discussions. This research was supported by the Israel-US Binational Science Foundation, an Israel Science Foundation Center of Excellence Award, and the Arnow Chair of Theoretical Astrophysics.

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