Magnetars in the Afterglow Era

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ABSTRACT. The X-ray afterglow that is observed following large flares on magnetars can be accurately fit by simple and quantitative theoretical models: The long term afterglow, lasting of order weeks, can be understood as thermal radiation of a heated neutron star crust that is re-scattered in the magnetosphere. Short term afterglow is well fit by the cooling of a non-degenerate, pair-rich layer, which gradually shrinks and releases heat to a pair-free zone above it. Measurements of persistent optical and infrared emission directly probe long lived currents in the magnetosphere which are a likely source of collective plasma emission. The superstrong magnetic field plays an important role in generating these various emissions, and previous inference of its strength in magnetars is supported by the good fits with observation.

1. Introduction

Magnetars exhibit a variety of revealing properties: They generate soft gamma ray bursts (SGR events) which typically last $\sim 80 - 200$ ms, and in extreme cases have super-Eddington luminosities, up to $10^7 L_{\text{Edd}}$. The brightest of these events reach peak luminosity within several milliseconds to a few seconds, and have observable tails that taper off within a few seconds to hundreds of seconds. This prompt burst emission is followed by short term X-ray afterglows lasting thousands of seconds, and, in some cases, longer term X-ray afterglows which persist for weeks or longer. Three AXPs have been discovered to emit optical and infra-red emission (Hulleman et al. 2000, 2001; Wang & Chakrabarty 2002). In one case, the optical emission is pulsed at the frequency observed in the X-ray bandpass (Kern & Martin 2002) and two other AXPs have shown longer timescale variability (of order weeks) in their IR flux coincident with episodes of burst activity (Kaspi et al. 2002a; Israel et al. 2002).

The light curve of some of the largest SGR bursts has been explained as a magnetically trapped pair fireball that shrinks to vanishing size (Thompson & Duncan 1995; Feroci et al. 2001). Usov (2001) has proposed that it is due to the cooling of a strange quark star surface just after heating by a GRB. Long term, transient X-ray afterglow has now been seen on two occasions from 1900+14, following large flares on Aug. 27, 1998 and April 18, 2001. The longest decay so far has been observed from 1627-41, lasting about 3 years (Kouveliotou et al., in preparation). The recent bursts from AXP 2259+586 also show prolonged X-ray afterglow (Kaspi, Gavriil & Woods 2002a,b).

Transient afterglow from neutron star surfaces following episodic energy releases was suggested by Eichler and Cheng (1989). Such emission could be useful for probing the crust of the neutron star as well as the depth of the energy release. There can be uplifting of surface material following a sufficiently powerful release of energy just below the surface, which is then radiated outward as short term afterglow. If the total energy release is sufficiently powerful and deep, then, although most of the heat is sucked into the star, some transient afterglow may be observed for weeks or months. The heat that is absorbed by the star reemerges as steady emission over human timescales.

Afterglow radiation also contains clues about the mechanism of SGR bursts: in particular, it is sensitive to the temperature to which the magnetosphere is heated during a burst (Thompson and Duncan 1995) and the manner in which the rigid crust of the star yields to magnetic stresses (Lyubarsky, Eichler, and Thompson 2002). The short term afterglow, with an observed $t^{-0.6}$ power law, can be explained as the cooling of
a pair-supported surface layer which is heated by exposure to an external fireball, and uplifted immediately thereafter. (Thompson, Woods, Eichler & Lyubarsky, in preparation). Heat deposited at depth (or conducted inward) may also contribute significantly to the persistent X-ray emission of magnetars: for example, the energy of a giant flare is roughly comparable to the persistent emission of the SGR integrated over its observed history.

The nonthermal infra-red and optical emission may be an important clue about relaxation of the magnetosphere. Eichler, Gedalin & Lyubarsky (2002) suggested that the infra-red and optical emission may be generated by coherent plasma processes in the magnetospheres of magnetars much as coherent radio emission is generated in pulsar magnetospheres.

2. Thermal relaxation of the crust and afterglows.

A soft gamma ray burst may involve not only a rearrangement of the magnetic field outside the neutron star, but also motion, deformation, and attendant heating of the crust itself. The timescale of any afterglow so induced depends on the depth to which the crust’s temperature is significantly raised by the SGR event. In order to study cooling of the magnetar crust, let us assume a deposition of thermal energy density of $\sim 1 \times 10^{25}$ erg cm$^{-3}$. This is near the maximum for which neutrino losses can be neglected, and it is comparable to the ratio of the flare energy ($\geq 1 \times 10^{44}$ ergs) to the volume of the neutron star. Within the crust, this energy density is less than a percent of $B^2/8\pi$, but greater than the pre-existing thermal energy density at depths less than $z_{\text{heat}} \sim 300$ m (for a likely internal temperature of $\sim 5 - 7 \times 10^8$ K; Thompson and Duncan 1996). If deposited over the entire surface and to a depth of $\sim 500$ m, this energy density implies a total energy of a few times the measured Aug. 27 afterglow energy. A characteristic feature of this heating mechanism is that the post-burst temperature increases outward in the heated layer, due to the strong crustal density stratification and inward heat conduction.

In our model, which attributes the fading of the afterglow to the cooling of the magnetar surface, the key issue is the heat transfer below the surface. The super-strong magnetic field significantly affects the structure of the upper crust. The Landau energy is relativistic in a $\sim 10^{15}$ G magnetic field, $E_L \approx 3B_{15}^{1/2}$ MeV when $B \gg B_{QED} = 4.4 \times 10^{13}$ G, and the electron Fermi energy, $E_F$, becomes comparable with the Landau energy only at a depth of $\sim 100$ m. At lesser depths electrons are one-dimensional.

Below a depth of a few meters, the heat is transferred by degenerate electrons. We calculated the electron thermal conductivity making use of the code developed by Potekhin (1999). The electron thermal conductivity, $\kappa$, has a prominent peak when $E_F$ is about the Landau energy. At larger density, $\kappa$ decreases, reaches a minimum when electrons become effectively 3-dimensional (at $z \sim 2 z_1$) and then grows slowly, as in the non-magnetized case. At small densities (at $z < z_1$), $\kappa$ rapidly decreases so that close to the surface the heat transfer is dominated by radiation. Close to the surface, $\kappa$ is so small that the heat resistance of the crust is dominated by the upper few meters. The outgoing thermal flux is formed within a “sensitivity strip” where the radiation thermal conductivities become comparable with the electron ones (Gudmundsson et al. 1983; Ventura & Potekhin 2001).

We have developed a code for simulations of time-dependent, one-dimensional heat transfer within the crust of the magnetar. The calculated outgoing flux is plotted, as a function of time, in Fig. 1 together with the data points obtained by Woods et al. (2001). The initial temperature distributions in curves 1 through 4 correspond to uniform heat density, with $T$ decreasing inward until it matched onto the initial (internal) value $T_{\text{int}}$. The heat density was normalized by the temperature $T_{\text{max}}$ at the bottom boundary of the skin zone. The remaining two curves show that the results are rather robust to...
varying the initial conditions. A slight “knee” occurs when the temperature maximum passes the minimum of the electron conductivity (at a few times $10^4$ s for $B = 10^{15}$ G).

Beyond this break, the light curve has a slope which is independent of $B$, because the thermal conductivity at greater depths approaches the $B = 0$ value. An “ankle” can occur beyond $10^6$ s, when the temperature maximum merges with the interior region of almost constant temperature.

We find that the transient X-ray light curve of SGR 1900+14 in the 40 days following the Aug. 27 event is consistent with the hypothesis that the SGR is a magnetar made of otherwise normal material. While there may be some freedom in choosing the heat deposition profile, the 40 day timescale is consistent with the basic physics of an outer crustal layer which is supported by relativistic degenerate electrons against gravity, and the heat capacity and conductivity increase considerably with depth. The power law index of the decay, though certainly inconsistent with a constant initial temperature, is found to be weakly sensitive to the exact initial temperature profile: on timescales more than a few days, the deeper layers are in any case cooled by inward conduction. Qualitatively, this causes all but $\sim 20$ percent of the heat to be sucked into the star and reradiated only over much longer timescales as surface X-ray emission or neutrinos. The resulting transient afterglow emission is $\sim 1$ percent of the flare energy, as observed (Woods et al. 2001), if the initial thermal energy density in the crust is comparable to the ratio of the flare energy to the volume of the neutron star. This is also consistent with the observation that the time integrated luminosity of the SGR is dominated by steady emission rather than by the decaying post-burst flux.

3. Short Term Afterglow: Cooling of the Pair Supported Atmosphere

The magnetically trapped fireball heats the surface layers of the crust and the absorbed heat is reradiated by surface photon emission after the the fireball has dissipated. The temperature of the fireball reaches about 1 MeV for the strong bursts; photons diffuse into the crust and heat up the surface layer of the depth about $10^9 - 10^{10}$ g/cm$^2$ (Thompson & Duncan 1995). This temperature is just enough to dissociate nuclei (including $^4$He). While the temperature is kept at 1 MeV by heating from above, the pressure is increased significantly over the initial hydrostatic pressure. This indicates that, in this conductive layer, the enthalpy per nucleon decreases with depth. After the hot magnetospheric plasma dissipates, the heated layer immediately expands, and the atmosphere is supported by the thermal pressure of the electron-positron pairs. The temperature is now low enough ($kT \sim 0.1 - 0.5 m_e c^2$) that helium quickly recombines, releasing up to $\sim 7$ MeV per nucleon. We assume here that most of the nuclear dissociation energy is restored before radiative cooling is complete. (See Thompson et al. 2003 for a more detailed discussion.) In this situation, the total extractable energy per nucleon $\varepsilon$ is constrained to a dynamic range of several: it is unlikely to be more than tens of MeV, in the absence of fine tuning, since otherwise the material would be blown off the star. To summarize the above, $\varepsilon$ is likely to lie in the range of a few to tens of MeV per nucleon, and to decrease slowly with depth. We normalize the column of material to an effective Thomson depth $\tau_T = \int_0^\Sigma \rho(z')dz'$ and choose

$$\varepsilon(\tau_T) = \varepsilon_0(\tau_T/\tau_{T,0})^{-\delta}.$$  

The atmosphere cools by photon diffusion. This process may be envisioned as a cooling wave, i.e. an entropy discontinuity at depth $z^*(t)$, which propagates inwards. We assume the strong magnetization provides stability against convection. A detailed analysis shows that the pair-rich zone is unstable to the formation of an annihilation front, above which (at $z \leq z^*$) the medium is essentially pair free (Thompson et al. 2003). Its specific enthalpy is well below that of the pair supported region, so that the flux which enters it from below mostly leaves the surface, and can therefore be taken to be constant at $z \leq z^*$. At the front of the wave, the annihilating pairs release the
Fig. 1. Flux times $4\pi \times 10^{12}$ cm$^2$ as a function of time. Curve 1 corresponds to $T_{\text{max}} = 5 \times 10^9$ K, $T_{\text{int}} = 7 \times 10^8$ K, $B = 10^{15}$ G; curve 2 to $T_{\text{max}} = 5 \times 10^9$ K, $T_{\text{int}} = 7 \times 10^8$ K, $B = 3 \times 10^{14}$ G; curve 3 to $T_{\text{max}} = 5 \times 10^9$ K, $T_{\text{int}} = 4 \times 10^8$ K, $B = 3 \times 10^{14}$ G; and curve 4 to $T_{\text{max}} = 3 \times 10^9$ K, $T_{\text{int}} = 4 \times 10^8$ K, $B = 3 \times 10^{14}$ G. The dotted curve 1' is for $B = 10^{15}$ G and an initial temperature distribution $T = 5 \times 10^9$ K at $z < 30$ m, and $5 \times 10^9 K(z/30m)^{-0.6}$ at $z > 30$ m; curve 2' is for $B = 3 \times 10^{14}$ G and $T = 5 \times 10^9$ K at $z < 100$ m, and proportional to $z^{-2}$ at greater depths until merging with the internal temperature of $7 \times 10^8$ K. Data points are from Woods et al. (2001). Squares are normalized to a distance of 9 kpc for SGR 1900+14 and triangles to 16 kpc.
energy $\varepsilon$ per nucleon, so that this constant flux is just

$$F = \frac{\varepsilon}{m_p} \frac{d\Sigma(z^*)}{dt}. \quad (1)$$

A detailed calculation shows that the temperature above the annihilation front varies slowly with depth, $T \simeq T_0 (\tau_T / \tau_{T,0})^\gamma$, with index $\gamma \simeq \frac{1}{3}$ and normalization $kT_0 \simeq \frac{1}{3}m_e c^2$ at $\tau_{T,0} = 10^8$. Therefore the outgoing flux varies with time mainly because the column of matter above the cooling wave front $\Sigma(z^*)$ increases with time.

In the super strong magnetic field, the radiation energy transfer is dominated by the extraordinary photons; their free path is very high and the Rosseland mean scattering cross-section is written as $\sigma(T, B) = 4\pi^2 \sigma_T (kT_0/m_e c^2)^2 (B_{QED}/B)^2$ (Silant’ev & Yakovlev 1980). The outgoing flux is

$$F = \frac{m_p c}{3Y_e \sigma(B, T) \partial \Sigma} = \frac{F_0}{\tau_T} \left( \frac{B}{B_{QED}} \frac{T}{T_0} \right)^2,$$  \quad (2)

where $U(T) = (1/2) aT^4$ is the energy density of the extraordinary photons, and $F_0 = a\epsilon T_0^3 (m_e c^2/k_B)^2/12\pi^2$. The energy balance equation (1) is now a differential equation for $\tau_T(z^*(t))$. With the above scaling between $\varepsilon$ and $\tau_T$, one finds $\tau_T(z^*(t))/\tau_{T,0} = [(8/5) - \delta] (Y_e/\tau_T^2 z_0) (B/B_{QED})^2 (F_0 \sigma_T/\varepsilon_0) t^{1/(8/5-\delta)}$, and

$$\frac{F}{F_0} = \left( \frac{B}{B_{QED}} \right)^{10(1-\delta)/(8-5\delta)} \tau_{T,0}^{(5\delta-2)/(8-5\delta)} \left[ \left( \frac{8}{5} - \delta \right) \frac{Y_e F_0 \sigma_T}{\varepsilon_0} t \right]^{-3/(8-5\delta)}. \quad (3)$$

For $0.4 \leq \delta \leq 0.75$, the obtained dependence of the outgoing flux on time is close to the overall $t^{-0.6}$ dependence (with slight fluctuations in the spectral index of order 0.1) observed from 1900+14 over $10^3$ s following the Aug 29, 1998 burst (Ibrahim et al. 2001, Lenters et al. 2003). The large temperature $(kT_{bb} \simeq 4$ keV) of that afterglow at $\simeq 10$ s following the burst points to a small radiative area (about 1 percent of the surface area of a neutron star) and a radiative flux $2 \times 10^{26}(kT_{bb}/4\text{ keV})^4$ erg cm$^{-2}$ s$^{-1}$. This implies

$$\frac{B}{B_{QED}} \simeq 10 \left( \frac{\varepsilon_0}{10\text{MeV}} \right)^{-3/4} \left( \frac{kT_{bb}}{4\text{ keV}} \right)^5,$$ \quad (4)

assuming $\delta = 0.6$.

4. Coherent Emission from Magnetars

Magnetars, it has been proposed (Thompson & Duncan 1996; Thompson, Lyutikov & Kulkarni, 2002), have twisted magnetic loops in their magnetospheres. Most of the time, the thermal scale height of their atmospheres is too low to populate the magnetosphere with thermal plasma. On the other hand, magnetospheric currents can easily be drawn out of the surface of the star from at least one of the footpoints. A modest rate of magnetic field dissipation $(d\ln B/dt \sim 1/10^3\text{yr})$ yields a sufficient potential drop across the length of the loop to create enough plasma to short out any larger potential drop. The density of plasma so estimated is many orders of magnitude larger than that in pulsar magnetospheres. If pulsars can radiate coherently in the radio, this frequency being ultimately determined by the plasma frequency in the pulsar magnetosphere, then similar processes could occur in magnetar magnetospheres with the plasma frequency scaled up appropriately.
The total density must clearly be at least as high as the minimum to deliver the required current,

\[ j = \frac{c}{4\pi} |\nabla \times B| \simeq ec \times [2 \times 10^{17} \frac{B_{15}}{R_6} \text{cm}^{-3}] \sin^2 \theta \Delta \phi_{N-S}. \]  

(5)

Here \( \theta \) is the magnetic polar angle and \( \Delta \phi_{N-S} \) is the relative twist (in radians) between the north and south magnetic poles. Because the above density greatly exceeds the co-rotation charge density, nearly equal numbers of positive and negative charges are required to avoid absurdly high electric fields. Positive charges may be supplied either by pulling ions off the surface of the star, or in situ through pair creation. In the second case, the particle density can exceed the above by a multiplicity factor \( \eta \) (which may be quite large; e.g. Hibschmann & Arons 2001).

That a two-species plasma is needed suggests that there is counterstreaming between the positive and negative charges. This gives rise to a broad band two stream instability. The excited plasma waves may be converted into outgoing electromagnetic waves (see, e.g., Gedalin, Gruman & Melrose 2002; Lyubarsky 2002). Regardless of the details of any particular counterstreaming model for the coherent emission, escaping coherent radiation probably has a frequency of the order of the plasma frequency in the frame of the outflowing plasma, which gives a frequency in the observer frame of \( 2 \omega_p \gamma^{1/2} \), where \( \gamma \) is the Lorentz factor, \( \omega_p \equiv (4\pi e^2 n/m_e) \) \( 1/2 \), \( n \) the plasma density in the laboratory frame, and \( m_e \) the rest mass of the electron.

The characteristic Lorentz factor of the plasma may be estimated as that which will give rise to charges of both signs, which is a necessary condition for shorting out the strong electric fields that would otherwise obtain. To create a pair plasma in this situation, one probably requires resonant scattering of thermal X-ray photons that emerge from the star’s surface.\(^1\) In order to be resonantly scattered by a relativistic electron moving in its lowest Landau level, thermal photons of energy \( \epsilon \) must have frequency of \( eB/\gamma m_e c \) in the electron rest frame – just as in sub-QED magnetic fields. Therefore a Lorentz factor of \( \gamma \sim (B/B_{QED}) (m_e c^2/\epsilon) \sim 10^3 (10 \text{keV}/\epsilon) B_{15} \) is needed.

Making use of the above estimates for the plasma density and Lorentz factor, one finds the frequency for coherent emission,

\[ \nu \sim \frac{1}{\pi} \gamma^2 \omega_p \sim 2 \times 10^{14} \left( \frac{\eta B_{15} \gamma^3}{R_6} \sin^2 \theta \Delta \phi_{N-S} \right)^{1/2} \text{Hz}. \]  

(6)

Near the surface, where \( B_{15} \sim 1 \), this suggests emission in the near IR, optical, or even UV for high enough \( \eta \) (Eichler, Gedalin and Lyubarsky, 2002). A twisted magnetic arch that protrudes from a magnetar surface could emit over a broad band, depending on the exact altitude of the emission. In the case where the current is supplied by electrons and ions, Lyutikov (2002) has suggested that coherent radio emission may be generated. (We note that strong emission at sub-millimeter wavelengths is plausible in this case.)

The coherent emission of pulsars is only a small fraction of the spin-down power, but it can be a much higher fraction of the power in polar currents, as the latter is itself only a small fraction of the total. By the same token, a considerable fraction of the long term magnetic energy dissipation in magnetars could end up as coherent electromagnetic emission; 1 to 10 percent is not unreasonable. A magnetar at a distance of up to 10 kpc could be detectable at 2.2 microns with imminent technology at a luminosity of \( 10^{33} \text{ erg/s} \) (\( \sim 10^{-2} \) of its persistent, pulsed X-ray flux). Such emission would almost certainly have the period of the magnetar, and would probably be polarized. In analogy

\(^1\) unless the magnetic field is extremely strong, \( B > 10^{16} \text{ G} \), and strongly sheared, in which case a pair corona can be maintained through multiple non-resonant Compton scattering (Thompson et al. 2002).
to pulsars, where the direction of polarization can swing with pulse phase, the time-integrated polarization would probably be less than that at any instant, but it could nevertheless be non-zero.

Is the optical emission (Hulleman, van Kerkwijk & Kulkarni 2000) from the anomalous X-ray pulsar 4U0142+61 coherent? On the one hand, this emission has been reported (Kern & Martin 2002) to have the periodicity of the AXP, which suggests that it arises from near the magnetar. With correction for reddening, the optical emission is about $10^{35}(D/3\text{Kpc})^2$ erg/s, and, because the emitting surface is so small, it is almost certainly non-thermal. On the other hand, general energetic and thermodynamical considerations still allow incoherent optical emission from neutron star magnetospheres at detectable levels (Eichler & Beskin 2000): A brightness temperature of up to $10^{12}(B/G)^{-1/7} \gg 10^6 T_\odot K$ is allowable in the case of emission by electrons, and this can in principle provide detectable optical emission from very small emitting areas. (The optical pulsar in the Crab exemplifies this.) The lower limit on the size of the emitting region is likely to come, in the case of electrons, from the constraints on the field strength set by the emission frequency and other considerations. The frequency and luminosity of the AXP optical/IR emission are also consistent with incoherent cyclotron radiation from a corona of hot ions beyond the radius of fast cyclotron cooling (about $30 R_{NS}$; Thompson et al. 2002).

Overall there are strong reasons to expect a substantial power in coherent plasma emission from the current-carrying magnetosphere of an AXP or SGR. Future tests that could conceivably establish coherence include a) ultra-fast photometry and polarimetry, which could reveal rapid time variability (micropulsation); b) pulsed infrared emission, which could set much higher floors for the brightness temperature; and c) polarization-time profiles, which could possibly distinguish between different coherent emission mechanisms. The peak frequency of this emission provides a strong diagnostic of the energy and composition of the charge carriers.

In conclusion, soft gamma ray repeaters and AXP's display a rich variety of transient, non-$\gamma$-ray emission that may be caused or otherwise affected by the SGR events. They seem to be very nicely explained by the the very same hypotheses that explained the SGR events themselves: that they are neutron stars with ultra-strong magnetic fields, that the SGR events are powered by magnetic energy release that can extend well into the neutron star crust, and that the magnetospheres are “twisted” and support long-lived currents. That the ultra-strong magnetic field $\sim 10^{15}$ G arises from quantitative fits to the data lends further support to the claim that the field is indeed so strong.

This research was supported by an Adler Fellowship from the Israel Science Foundation, the Arnow Chair of Theoretical Astrophysics, the Israel Ministry of Absorption, and the NSERC of Canada. We acknowledge helpful conversations with C. Kouveliotou.

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