PHOTOSPHERIC RADIUS EXPANSION DURING MAGNETAR BURSTS

ANNA L. WATTS1, CHRYSSA KOUVELIOTOU2, ALEXANDER J. VAN DER HORST3,7, ERSIN GÖGÜS4, YUKI KANEKO4, MICHEL VAN DER KLIS1, RALPH A. M. J. WIJERS1, ALICE K. HARDING3, and MATTHEW G. BARING6

1 Astronomical Institute “Anton Pannekoek,” University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands; A.L.Watts@uva.nl
2 Space Science Office, VP62, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA
3 NASA Marshall Space Flight Center, Huntsville, AL 35805, USA
4 Sabancı University, Orhanlı–Tuzla, Istanbul 34956, Turkey
5 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
6 Department of Physics and Astronomy, MS-108, Rice University, P.O. Box 1892, Houston, TX 77251-1892, USA

Received 2010 March 23; accepted 2010 June 10; published 2010 July 19

ABSTRACT

On 2008 August 24 the new magnetar SGR 0501+4516 (discovered by Swift) emitted a bright burst with a pronounced double-peaked structure in hard X-rays, reminiscent of the double-peaked temporal structure seen in some bright thermonuclear bursts on accreting neutron stars. In the latter case this is due to Photospheric Radius Expansion (PRE): when the flux reaches the Eddington limit, the photosphere expands and cools so that emission becomes softer and drops temporarily out of the X-ray band, re-appearing as the photosphere settles back down. We consider the factors necessary to generate double-peaked PRE events, and show that such a mechanism could plausibly operate in magnetar bursts despite the vastly different emission process. Identification of the magnetic Eddington limit in a magnetar would constrain magnetic field and distance and could, in principle, enable a measurement of gravitational redshift. It would also locate the emitting region at the neutron star surface, constraining the burst trigger mechanism. Conclusive confirmation of PRE events will require more detailed radiative models for bursts. However, for SGR 0501+4516 the predicted critical flux (using the magnetic field strength inferred from timing and the distance suggested by its probable location in the Perseus arm of our Galaxy) is consistent with that observed in the August 24 burst.

Key words: pulsars: individual (SGR 0501+4516) – stars: neutron – stars: magnetic field – X-rays: bursts

1. INTRODUCTION

Type I X-ray bursts are thermonuclear explosions caused by unstable burning of light elements in the surface layers of accreting neutron stars (for a review see, e.g., Lewin et al. 1993). Luminosities frequently reach the Eddington limit, at which point radiation pressure lifts the surface layers from the star in a Photospheric Radius Expansion (PRE) episode. One of the hallmarks of bright PRE bursts, when observed with sufficient time resolution, is a pronounced double-peaked structure in the X-ray light curve (Hoffman et al. 1978, 1980; Paczyński 1983; Ebisuzaki et al. 1984; Lewin et al. 1984; Tawara et al. 1984; Vacca et al. 1986; Haberl et al. 1987). As the photosphere moves outward the temperature drops and the energy of the emitted photons falls below the X-ray band, leading to an apparent drop in count rate. As the photosphere contracts again the temperature rises, and there is a second brighter peak in X-ray emission (Paczyński 1983). If one looks at the bolometric rather than the X-ray light curve, the double-peaked structure almost completely disappears.

PRE bursts have proven extremely useful in studies of accreting neutron stars since they act as standard candles, yielding distance (van Paradijs 1978, 1981; Kuulkers et al. 2003; Galloway et al. 2003, 2006). PRE events can also be used to place constraints on mass and radius, and hence the dense matter equation of state (see, for example, Damen et al. 1990a, Galloway et al. 2008b and Özel et al. 2009).

On 2008 August 24 the newly discovered magnetar SGR 0501+4516 (Barthelmy et al. 2008) emitted a bright burst with a pronounced double-peaked structure (Figure 1). This motivated us to consider whether multi-peaked PRE events might be possible in magnetar bursts, despite the vastly different emission mechanism (magnetic rather than thermonuclear). The existence of a magnetically modified Eddington limit has been discussed in the literature for a number of years (Paczyński 1992; Ulmer 1994; Thompson & Duncan 1995; Miller 1995; Israel et al. 2008a). However, the prospect of PRE and multi-peaked burst light curves has never been considered before, perhaps in part due to the considerable uncertainty that still exists over the magnetar burst trigger and emission mechanism.

We start in Section 2 with the thermonuclear burst case, and identify the factors essential to the generation of double-peaked PRE bursts. In Section 3, we move on to magnetar bursts, and consider whether there are burst emission scenarios where these conditions might be met. We conclude that PRE events might plausibly occur in magnetar bursts under certain circumstances. In Section 4, we consider what could be learnt from an unambiguous identification of a PRE magnetar burst. In addition to constraining stellar properties (as for the X-ray burst case) it would also constrain the burst trigger and emission mechanism.

In Section 5, we return to the event that motivated our study and ask whether the bright burst from SGR 0501+4516 on 2008 August 24 could be an example of PRE. We show that the predicted critical flux, using the magnetic field strength inferred from timing and the distance suggested by its probable location in the Perseus arm of our Galaxy, is consistent with that observed. Confirmation, however, requires the development of more detailed radiative models for the bursts. In Section 6, we broaden our scope to include the other magnetars, and assess whether we could or should have seen PRE episodes from these sources. The magnetar population includes objects classified as...
2. PRE IN THERMONUCLEAR X-RAY BURSTS

For thermonuclear bursts to exhibit PRE and for the X-ray light curve to be double-peaked, four basic conditions must be met.

1. Flux has to be emitted from an optically thick region.
2. There must be a critical luminosity where radiation pressure can balance gravitational and other confining forces on the emitting matter.
3. Opacity must increase with radius.
4. The emitting region must cool as the photosphere expands.

2.1. Condition 1: Location of Emitting Region

In order for there to be a photosphere, the initial emission has to occur in an optically thick region and propagate outward. For X-ray bursts this condition is easily met, since the thermonuclear runaway that triggers the burst can only occur at the base of the neutron star ocean, where density $\sim 10^6$ g cm$^{-3}$ (see Bildsten 1998, and references therein). In this regime optical depth is much greater than unity and a photosphere will exist.

2.2. Condition 2: The Existence of a Critical Luminosity

The critical, or “Eddington” luminosity can be calculated by considering the balance between radiation pressure and gravity in the emitting matter. For accreting neutron stars we can neglect other confining forces since magnetic fields are weak. If the accreting material is fully ionized, then radiation exerts a force primarily on the electrons via Thomson scattering. Coulomb attraction between protons and electrons means that radiation must act against a gravitational force set predominantly by the nuclear mass. Under these conditions, force balance in Newtonian gravity yields

$$L_{\text{Edd}} = \frac{4\pi c GM}{\kappa}, \quad (1)$$

where $M$ is the gravitational mass of the neutron star (see Lewin et al. 1993, and references therein). For non-magnetic systems subject only to Thomson scattering, the opacity $\kappa$ is defined as

$$\kappa = \frac{\sigma_T n_e}{\rho}, \quad (2)$$

where $\sigma_T$ is the Thomson cross section, $n_e$ the number density of electrons, and $\rho$ the density. The precise value of $\kappa$ depends on the composition of the accreted material due to contributions in the X-ray band from bound-free transitions for heavier elements. As we shall see in Section 3, the intense magnetic field in magnetars introduces profound modifications to the determination of $\kappa$. For thermonuclear bursting sources, the inferred magnetic fields are too low to have such an effect.

When considering observable quantities, we need to take into account how General Relativity modifies this expression. The gravitational force is stronger by a factor $(1 + z)$ where

$$1 + z = \left(1 - \frac{2GM}{Rc^2}\right)^{-1/2}$$

and $R$ is the radial distance from the center of the neutron star as measured by a local observer (Lewin et al. 1993). This modifies the force balance equation, and means that the critical luminosity as measured by a local observer at the photosphere$^8$

$$L_{\text{Edd}} = \frac{4\pi c GM}{\kappa(1 + z)}, \quad (3)$$

For an observer at infinity,

$$L_\infty = L_{\text{ph}}(1 + z_{\text{ph}})^{-2}, \quad (4)$$

where the subscript “ph” refers to the photosphere. This means that for a distant observer,

$$L_{\text{Edd},\infty} = \frac{4\pi c GM}{\kappa(1 + z_{\text{ph}})} \quad (5)$$

$^8$ Calculations and observations show that the outflow velocities are much smaller than the speed of light (Ebisuzaki et al. 1983; Kato 1983; Paczyński & Prószyński 1986; Joss & Melia 1987; in ’t Zand & Weinberg 2010). This means that the difference between the luminosity measured by an observer moving with the photosphere, and by a stationary observer at the same radial distance, can be neglected.
(Lewin et al. 1993). For typical neutron star parameters \((M = 1.4 \, M_\odot, R_\star = 10 \, \text{km})\) and solar to He-rich composition for the accreting material, this yields \(L_{\text{Edd,\infty}} \approx (2 - 3.7) \times 10^{38} \, \text{erg s}^{-1}\) at touchdown (when \(R = R_\star\)). This value is comparable to the luminosities observed during the brightest Type I X-ray bursts (Kuulkers et al. 2003; Galloway et al. 2008a).

2.3. Condition 3: Increase in Opacity with Radius

The local critical luminosity falls as radius increases, as \((1+z)\) (Equation (4)). However, the luminosity of the propagating photons also falls, as \((1+z)^2\) (Equation (5)). These General Relativistic (GR) effects impose further conditions on the occurrence of PRE bursts. Consider what would happen if the opacity were constant in the atmosphere. In this case, the ratio of the luminosity to the critical luminosity would vary with radius as

\[
\frac{L}{L_{\text{cr}}} \propto (1 + z)
\]

reducing outward (Paczyński & Anderson 1986). The luminosity emerging from the photosphere would not reach the critical value unless the luminosity at depth exceeded the local limit. This could only be achieved via convection, which would largely prevent envelope (and hence photospheric radius) expansion (Paczyński & Anderson 1986; Woosley et al. 2004; Weinberg et al. 2006).

This problem can only be bypassed if the critical luminosity is higher at greater depths within the photosphere. It turns out that this is possible, because opacity depends on temperature \(T\) (Hanawa & Sugimoto 1982) when Klein–Nishina modifications become significant. The opacity should more properly be written as

\[
\kappa = \frac{k_0}{1 + (2.2 \times 10^{-9} T^{0.86})}
\]

(Paczyński 1983), where \(k_0\) is the non-magnetic Thomson opacity given in Equation (2). The burning layer is hotter \((>10^9 \, \text{K even at ignition, up to} \sim 10^9 \, \text{K during the burst})\) than the photosphere \((\sim 10^7 \, \text{K})\), so the opacity is much lower at greater depths, i.e., lower altitudes. This permits a high flux to propagate out of the hot burning layer without a large convective zone being present.

The increase in opacity with altitude as the plasma cools is also essential for sustained photospheric radius expansion to occur. If this were not the case then once the photosphere started to expand and cool (Section 2.4), the ratio \(L/L_{\text{cr}}\) would quickly drop below unity, halting expansion. We note in passing that in the magnetar application (Section 3), the gradients of the magnetic field define a stronger dependence of opacity and associated critical luminosity on altitude than the gravitational redshift influences identified here.

2.4. Condition 4: Cooling of Emission Region with Expansion

To obtain a double-peaked X-ray light curve, the photosphere must cool as it expands in response to radiation pressure. For X-ray bursts this is thought to occur because the emission is quasi-blackbody, and the luminosity at the photosphere remains close to critical. For blackbody emission

\[
L_\infty = 4\pi (R_\infty)^2 \sigma (T_{\text{eff,\infty}})^4.
\]

where \(\sigma\) is the Stefan–Boltzmann constant, \(R_\infty = R(1+z_{\text{ph}})\) is the photospheric radius as measured by the distant observer, and \(T_{\text{eff}}\) is the effective temperature (Rybicki & Lightman 2004). If photospheric luminosity remains at the critical value given by Equation (4), as suggested by theoretical simulations (Paczyński 1983; Kato 1983; Ebisuzaki et al. 1983; Ebisuzaki et al. 1984; Quinn & Paczyński 1985; Paczyński & Anderson 1986; Paczyński & Prószynski 1986; Joss & Melia 1987; Nobili et al. 1994; Weinberg et al. 2006), then we obtain

\[
T_{\text{eff,\infty}} = \left[ \frac{cGM}{\sigma k} \right]^{1/4} R^{-1/2} (1+z)^{-3/4}. \tag{10}
\]

The redshift factor \((1+z)^{-3/4}\) increases as the photosphere expands, but more slowly than the \(R^{-1/2}\) factor, so the observed temperature \(T_{\text{eff,\infty}}\) falls as \(R\) increases.

How well does this simple model hold up for real X-ray bursts? X-ray bursts are indeed generally well fit by a blackbody spectrum (Swank et al. 1977; Lewin et al. 1993; Galloway et al. 2008a), although there are some deviations (Damen et al. 1989, 1990a, 1990b; van Paradijs et al. 1990; Kuulkers et al. 2003). Spectral fitting to multi-peaked PRE bursts supports the picture of temperature falling as radius expands, although again there are some minor discrepancies in the observations. Bolometric luminosity, for example, often continues to rise all the way through until touchdown at the surface, rather than rising and then falling, as predicted by Equation (6) (Galloway et al. 2008a). There has yet to be any serious systematic effort to quantify and resolve the remaining discrepancies; however, non–Planckian spectra (van Paradijs 1982), compositional effects (Galloway et al. 2006), obscuration or scattering by the accretion flow (Damen et al. 1990b; Galloway et al. 2008b), and clearing of the inner parts of the disk by the expanding photosphere (Shaposhnikov et al. 2003) may all play a role.

3. PRE IN MAGNETAR BURSTS

Magnetar burst fluxes follow a power-law distribution \((\log N \sim \log S)\) with an index of \(\sim -1.7\) (see Woods & Thompson 2006; also Göğüş et al. 2001). The bulk of this emission is in weak, soft events that occur in bunches during a burst-active episode. At times several hundreds of these bursts have been recorded during a 24 hr period of magnetar activity. Occasionally, sources emit much brighter events (intermediate bursts) and very rarely, giant flares—only three of the latter have ever been recorded. Small burst luminosities vary between \((10^{-2} - 10^3) \, L_{\text{Edd}}\), while the giant flare luminosities can reach up to \(10^7 \, L_{\text{Edd}}\), where \(L_{\text{Edd}}\) is the non-magnetic Eddington limit. To determine whether any of these apparently super-Eddington bursts could in principle exhibit multi-peaked behavior due to PRE episodes, we must assess whether the four conditions necessary for the occurrence of this phenomenon, identified in Section 2, can be met by magnetars. It is possible, of course, that additional conditions may have to be met for PRE to operate during magnetar bursts: however, it seems reasonable to start with the four conditions that we know are required for PRE to occur in thermonuclear X-ray bursts.

The magnetar problem differs from the X-ray burst problem in several key respects. The burst mechanism is magnetic rather than thermonuclear, but there is as yet no agreement on the trigger mechanism or emission site location. The strong magnetic field alters many of the emission properties (Harding & Lai 2006): in particular, scattering depends on polarization, with \(E\)-mode (electric field vector polarized perpendicular to the magnetic field) scattering suppressed compared to the \(O\)-mode scattering (electric field vector parallel to the magnetic field) unless photons stream along field lines. The situation will
also change depending on whether we are discussing emission from open or closed field line regions, since radiative transport across magnetic field lines is strongly inhibited relative to that along fields in neutron star magnetospheres. We will examine the various scenarios that are currently envisaged, and assess whether there are any circumstances under which multi-peaked PRE behavior might be possible.

3.1. Condition 1: Location of Emitting Region

There is consensus that the underlying cause of the bursting activity (as well as many other magnetar properties) is the decay of the strong magnetic field (Woods & Thompson 2006). This results in the field twisting into a configuration that eventually becomes unstable (Braithwaite & Nordlund 2006; Braithwaite & Spruit 2006). The bursts are generated by rapid rearrangement of the magnetic field, and the formation and dissipation of localized currents. External reconfiguration is likely to involve reconnection (due to the many instabilities that can operate in a plasma) although this may not occur in all bursts (Duncan 2004). What is not clear yet is exactly where the dissipation and emission occurs: in the crust, at the surface of the star, high in the magnetosphere, or a combination of all three? For a well-defined photosphere to exist emission must come from an optically thick region, so emission in an optically thin region would not be compatible with the multi-peaked PRE hypothesis.

Part of the uncertainty over the emission region stems from the fact that the trigger for magnetar bursts is still not known. For there to be sporadic bursting activity, there has to be some barrier to magnetic reconfiguration that yields on the rise of the strong magnetic field (Woods & Thompson 2006). This results in the field twisting into a configuration that eventually becomes unstable (Braithwaite & Nordlund 2006; Braithwaite & Spruit 2006). The bursts are generated by rapid rearrangement of the magnetic field, and the formation and dissipation of localized currents. External reconfiguration is likely to involve reconnection (due to the many instabilities that can operate in a plasma) although this may not occur in all bursts (Duncan 2004). What is not clear yet is exactly where the dissipation and emission occurs: in the crust, at the surface of the star, high in the magnetosphere, or a combination of all three? For a well-defined photosphere to exist emission must come from an optically thick region, so emission in an optically thin region would not be compatible with the multi-peaked PRE hypothesis.

In the crust failure model, a recurrent trigger would require a network of crust ruptures, with a slip along one “fault” setting off the next. The activity would have to be confined to a relatively small part of the stellar surface, since if the rupture spread rapidly to the far side of the star then the slow rate of rotation would ensure that any emission close to the surface would disappear from view. The possibility of avalanches of reconnection is discussed by Lyutikov (2003) in the context of the magnetospheric trigger model. In this picture emission probably does not take place in an optically thick region unless precipitating particles generated by the avalanche impact the surface. The heated surface would then radiate on a thermal timescale.

The alternative is some kind of storage mechanism that leads to emission over a longer period. Two possibilities have been discussed in the literature: crust vibrations, and the formation of a trapped pair-plasma fireball. In the crust vibration model the initial impulse excites torsional oscillations of the crust (Duncan 1998). This is known to occur in the rare and highly energetic giant flares (Israel et al. 2005; Strohmayer & Watts 2005, 2006; Watts & Strohmayer 2006), although vibrations have not yet been detected after the regular bursts. The excitation of crust vibrations is certainly plausible if the trigger is crust failure; whether vibrations could be excited to a significant degree by magnetospheric reconnection alone is less clear. The oscillating crust couples (via the charged lattice) to the field lines, generating Alfvén waves which lead to particle acceleration and prolonged emission. Where in the magnetosphere this excitation and emission might occur would depend on the amplitude of the oscillations, with larger motions coupling to longer field lines. If the motions are strong enough, however, the energy available may be sufficient to generate an optically thick pair plasma. For very high release rates this may lead to trapped fireball formation (see below) but for slower injection rates the plasma can form an optically thick corona in which there is a steady balance between injection rate and radiation rate. This effect has been invoked to explain the initial smooth tail in the giant flare light curves (Thompson & Duncan 2001), and Göğüş et al. (2001) have discussed its possible role in the smaller bursts.

The other possibility is the formation of a magnetically trapped, optically thick fireball that gradually leaks radiation. Thompson & Duncan (1995) argued that such a phenomenon was an inevitable consequence of very rapid energy generation in a closed field line region. This could be due to either reconnection (Thompson & Duncan 1995) or the development of a Quantum Electrodynamic (QED) shock (Heyl & Hernquist 2005). A fireball could therefore be formed from either of the two trigger mechanisms provided that the local energy generation rate is high enough and within a closed field line region. The rapid generation of Alfvén waves or relativistic particles leads to the formation of a dense optically thick thermal plasma of $e^\pm$ pairs and $\gamma$ rays. The charged pairs effectively cannot cross the magnetic field lines, and their density (and hence scattering opacity) is sufficiently high that they trap radiation. The fireball cools and contracts due to radiative diffusion from a thin surface layer, with the bulk of the radiation leakage occurring close to the stellar surface where scattering is suppressed (see Section 3.2). The opacity here will be dominated by electrons and ions ablated from the neutron star surface (especially if the emergent flux is close to the magnetic Eddington limit) which form the photosphere. The heated surface exposed as the fireball retreats will also continue to emit radiation as it cools.

The fireball model has been very successful at explaining the later decaying tail phase of giant flares (Thompson & Duncan 2001). Spectral fitting indicates that the emitting area falls while the temperature of the radiation remains roughly constant at the level expected for the photosphere of a trapped fireball in a magnetic field in excess of $B_{\text{QED}} = 4.4 \times 10^{17}$ G (Thompson & Duncan 1995; Feroci et al. 2001). In the early
stages (the “smooth tail”) the photosphere is dominated by pairs (see above), while in the later stages it reverts to one dominated by electrons and ions ablated from the stellar surface. Whether fireballs form in the smaller bursts is still not clear (energy release may not occur at a fast enough rate, Göğüş et al. 2001), although the spectra are similar to those of the decaying tails of the giant flares (Woods & Thompson 2006).

To summarize, however, there are viable scenarios for both optically thick and optically thin emission. In the magnetospheric instability picture optically thick emission is much less likely. Within the crust slippage model emission may occur from optically thick regions, particularly if (1) reconnection occurs in or close to the surface layers, or (2) a trapped fireball or pair corona forms. In this case the formation of a well-defined photosphere is possible. In fact, as we will see in Section 3.2, the two different polarization modes will have spatially distinct photospheres due to their different scattering properties.

### 3.2. Condition 2: The Existence of a Critical Luminosity

Scattering opacities in a magnetar strength field are strongly modified compared to the non-magnetic case outlined in Section 2.2. In closed field line regions, the magnetic field can also provide an additional non-negligible confining force to balance radiation pressure. Both of these factors increase the Eddington limit.

#### 3.2.1. Reduction in Scattering

Paczyński (1992) was the first to address the apparently super-Eddington luminosities emitted during SGR bursts. He considered the case of energy release deep within the surface layers, with photons diffusing out at a rate limited by electron conductivity or photon opacity. In a magnetic field \( B \) both Thomson and Compton cross sections are reduced for photon energies \( E_\nu = h\nu \) lower than the electron cyclotron energy \( E_c \), where

\[
E_c = h\omega_c = 11.58 \text{keV} \left(\frac{B}{10^{12} \text{G}}\right),
\]

because electrons cannot easily move perpendicular to the magnetic field. Consider the case where \( (E_\nu/E_c)^2 \ll 1 \), a condition that is generally met for magnetar bursts in the energy bands that we are considering; the cyclotron energy \( E_c \) for the fundamental Compton scattering resonance falls in the X-ray band only at altitudes of \( \gtrsim 20 \) stellar radii for magnetars. For the \( O \)-mode the scattering cross section is

\[
\sigma_{||}/\sigma_T \approx \sin^2 \theta + \left(\frac{E_\nu}{E_c}\right)^2 \cos^2 \theta,
\]

where \( \theta \) is the angle between the direction of propagation of the photons and the magnetic field. For the \( E \)-mode,

\[
\sigma_{\perp}/\sigma_T \approx (E_\nu/E_c)^2.
\]

These magnetic Thomson domain results can be deduced from Equation (16) of Herold (1979). Full QED numerical evaluations of the polarization-averaged magnetic Compton cross section are displayed for different \( \theta \) in Figure 3 of Herold (1979) and Figure 3 of Daugherty & Harding (1986).

Scattering is therefore suppressed for both polarizations for radiation flowing along open field lines, and is always suppressed for the \( E \)-mode. This means that the \( E \)-mode and \( O \)-mode photospheres will be spatially distinct whenever the polarization states are decoupled, with the \( E \)-mode photosphere extending deeper into the surface layers. If polarization mode-switching via scattering is prolific, then the two photospheric scales become coupled, a nuance that is addressed below.

A useful quantity for estimating the radiative flux at large optical depth is the Rosseland mean opacity \( \bar{\kappa} \), where

\[
\frac{1}{\bar{\kappa}} = \left[ \int_0^\infty \frac{1}{\kappa_T} \frac{\partial B_\nu(T)}{\partial T} d\nu \right] \left/ \left[ \int_0^\infty \frac{\partial B_\nu(T)}{\partial T} d\nu \right] \right..
\]

In this expression, \( \kappa_T \) is the monochromatic opacity at the photon frequency \( \nu = \omega/2\pi \), and \( T \) is the temperature. In field-free regions, \( \kappa_T \) can be represented by Equation (2) or Equation (8). The function \( B_\nu \) is the Planck function (Rybicki & Lightman 2004). For the highly anisotropic conditions imposed by the strong magnetar fields, \( \kappa_T \) represents a weighted average over photon angles with respect to the magnetic field. However, it should be remarked that technically the Rosseland mean opacity is most conveniently employed for almost isotropic photon populations, i.e., applied to radiative transfer problems in the interiors of normal stars. Notwithstanding, it is still a useful measure, and here, as expected, \( \kappa_T \) is lowest for photons streaming along field lines. Note also that for X-ray bursts (Section 2.2) there is no need to use the Rosseland mean opacity, because the scattering cross section \( \sigma_T \) does not depend on photon energy. Hereafter, \( \bar{\kappa} \) can be interpreted as a photon polarization-dependent quantity, or as an average of photon polarizations, as needed.

Equation (1) for the critical luminosity now becomes

\[
L_{\text{crit}} = \frac{4\pi c G M}{\bar{\kappa}},
\]

This magnetic Eddington luminosity depends on magnetic field strength and temperature as well as the stellar parameters. For photons streaming along field lines it follows that

\[
L_{\text{crit}} \approx \left( \frac{\omega_c}{\omega} \right)^2,
\]

where \( L_{\text{Edd}} \) is as given in Equation (1). Anisotropies and, as we shall see below, mode switching between polarizations will profoundly influence this ratio.

To compute \( L_{\text{crit}} \), Paczyński (1992) uses the fact that \( \omega = kT/\hbar \) and then assumes blackbody emission, so that the critical flux \( F_{\text{crit}} = \sigma T^4 \). Under this assumption, and using Equation (1) for \( L_{\text{Edd}} \), one can rewrite Equation (16) as

\[
L_{\text{crit}} \approx 2 \left( \frac{B}{10^{12} \text{G}} \right)^{4/3} \left( \frac{g}{2 \times 10^{14} \text{cm s}^{-2}} \right)^{-1/3}.
\]

This is the estimate used for magnetic Eddington limit in, for example, Israel et al. (2008a).

Subsequent authors have revisited this calculation and made a number of corrections and additions. Thompson & Duncan (1995), for example, noted that Equation (13) is only valid when plasma density is low (Herold 1979). If plasma density is higher (so that the plasma frequency approaches the cyclotron frequency), as it might be for surface rather than magnetospheric emission, the scattering cross section is higher (see also Mészáros 1992 and Miller 1995). For emission from the neutron star surface, Equation (13) would become

\[
\sigma_{\perp}/\sigma_T \approx \frac{1}{\sin^2 \theta} \left(\frac{E_\nu}{E_c}\right)^2.
\]
increasing the scattering cross section of the E-mode. Thompson & Duncan (1995) recompute the magnetic Eddington limit for this cross section, again assuming blackbody emission. The coefficients that they find are slightly different to those derived by Paczyński (1992), but to a factor of order unity Equation (16) still applies.

Ulmer (1994) and Miller (1995) considered the important effect of scattering between polarization states on the critical luminosity. Miller (1995) demonstrated that the emergent luminosity is dominated by E-mode photons, since O-mode photons above the E-mode photosphere will continue to scatter into the E-mode and then escape from the star. The radiation force, however, is dominated by the O-mode due to the much higher scattering cross section. Miller (1995) uses order of magnitude estimates of the mode scattering to show that the luminosity which eventually emerges in the O-mode, \( L_{\|} \), is given by

\[
L_{\|} \sim 0.1 \omega_c^2 \sigma T L_{\text{tot}},
\]

where \( L_{\text{tot}} \) is the total luminosity in both polarization states. For the small number of photons that end up in this state, the scattering cross section \( \sim \sigma T \) (Equation 12). For the atmosphere to remain hydrostatic, one requires \( L_{\|} < L_{\text{Edd}} \) so that

\[
L_{\text{tot}} \lesssim 10^4 (\omega_c / \omega) L_{\text{Edd}}.
\]

This estimate, which was then verified using Monte Carlo simulations of radiative transfer (Miller 1995), is lower than that obtained by Paczyński (1992) and Thompson & Duncan (1995).

The critical luminosity may in fact be lower still due to other scattering processes that operate in a magnetized neutron star atmosphere including vacuum polarization and mode switching, the proton cyclotron resonance, and bound-free absorption (Miller 1995; Thompson et al. 2002). Photon splitting will also increase the fraction of O-mode photons, further increasing the radiation force (Miller 1995; Thompson & Duncan 2001). One additional factor that none of the above calculations include is the effect of gravitational redshift, something that is taken into account in all of the estimates of critical flux for X-ray bursts (Section 2.2). This should be included in the estimates of observed critical luminosity if the photosphere is close to the neutron star surface. Such general relativistic corrections can be introduced by an effective blueshift to the photon frequency entering into Equations (16) or (20) that acts to reduce the critical luminosity. However, the enhancement of the magnetic field strength in the local inertial frame (see, e.g., Gonthier & Harding 1994 for the dipolar case) partially offsets this reduction by effectively blueshifting the cyclotron frequency.

### 3.2.2. Magnetic Confinement Effects

In Section 3.2.1, we saw that the magnetic field reduces scattering for radiation propagating both parallel to and across field lines, increasing the critical flux over the non-magnetic limit derived in Section 2.2. In this section, we will consider the effect of magnetic confinement. The magnetic field resists the motion of charged particles across field lines, thereby contributing an additional term to the force balance equation and increasing the critical flux for closed field line regions.

The field necessary to confine the plasma can be estimated by requiring that magnetic pressure exceed radiation pressure (assuming that radiation pressure dominates gas pressure):

\[
\frac{B^2}{8\pi} \gg \frac{\beta}{c} \sigma T^4,
\]

where \( \beta \) depends on the angular distribution of the radiation field: it is one-third for isotropic radiation (Lamb 1982). Note that this estimate is only valid for blackbody radiation, though it can be readily adapted to treat any luminosity per unit area passing through a surface element. This simplifies (Ulmer 1994; Miller 1995) to the requirement that

\[
\left( \frac{B}{10^{12} \text{ G}} \right) \gtrsim \left( \frac{T}{170 \text{ keV}} \right)^2.
\]

For magnetar bursts this condition is met provided the photospheric radius is below about 10 stellar radii. Note that because magnetic pressure acts perpendicular to the field, plasma can always move rapidly along field lines. In such cases, using a magnetohydrodynamic interpretation for the electromagnetic contribution to the stress-energy tensor, the left-hand side of Equation (22) is replaced by a much smaller combination of the field and the plasma speed. Hence, in order to achieve confinement one therefore needs closed field geometries, and even in this case matter will migrate toward the points where the field is weakest. For a dipole field this means toward the equator, and away from the stellar surface.

In the closed field line regions matter can be confined out to the point where the pressure of free streaming photons exceeds the dipole magnetic energy density. At this radius, the optical depth will drop to \( \ll 1 \). Thompson et al. (2000) showed that this occurs for radii greater than \( R_\Delta \) where

\[
R_\Delta \sim 280 \left( \frac{B}{10 \text{ G}} \right)^{1/2} \left[ \left( \frac{10^{44} \text{ erg}}{E_\text{burst}} \right) \left( \frac{100 \text{ s}}{\Delta t_{\text{burst}}} \right) \right]^{1/4}.
\]

\( E_\text{burst} \) and \( \Delta t_{\text{burst}} \) are the energy and duration of the burst, respectively. For typical SGR bursts, \( R_\Delta \gg R_* \). So in a closed field line region, emitting plasma can be confined close to the stellar surface for luminosities far in excess of the values derived in Section 3.2.1 for open field line regions.

#### 3.3. Condition 3: Increase in Opacity with Radius

In Section 2.3, we showed that GR effects would stifle PRE unless opacity increased with altitude. The same GR effects must apply to magnetar bursts if the emission site is close to the stellar surface. For X-ray bursts the variation in opacity with depth comes from the temperature dependence of opacity. For magnetar bursts the magnetic field dependence of the opacity (Section 3.2.1) can provide a similar, albeit much stronger, effect.

The magnetic field strength quickly falls off with radius (for a dipole field as \( 1/R^3 \)), leading to a rapid increase in opacity with height above the stellar surface. Evidence of this increase in scattering comes from the strong rotational pulse profiles seen during the decaying tails of light curves from the giant flares. Radiation emitted from the base of a trapped fireball (Section 3.1) is thought to be collimated by the increase in scattering opacity, forming highly focused jets of X-ray emission (Thompson & Duncan 1995, 2001).

#### 3.4. Condition 4: Cooling of Emission Region with Expansion

For thermonuclear bursts the expansion and cooling of the emitting region follows very simply from the fact that the emission is, for the most part, well modeled by a blackbody (Section 2.4). Demonstrating that the emitting region is expanding and cooling for magnetar bursts is not as straightforward.
Although the majority of magnetar bursts are relatively soft (compared to gamma-ray bursts, for example, although not to X-ray bursts; see Woods & Thompson 2006), they are not well fit by simple blackbody spectra.\(^9\) Multi-component spectral models containing one or two blackbodies have had some success (Feroci et al. 2004; Olive et al. 2004; Nakagawa et al. 2007; Esposito et al. 2007; Israel et al. 2008a; Esposito et al. 2008) but it is not yet clear to what extent these models are physical rather than phenomenological.

The failure of simple blackbody models is however not unexpected, since radiative transfer effects in such strong magnetic fields should substantially modify any initially thermal spectrum, of the type that we might expect, for example, from a trapped fireball (Thompson & Duncan 1995, 2001) or other optically thick region (Paczyński 1992). Lower energy photons, for example, scatter less and can hence escape from deeper, hotter parts of the atmosphere. The radiation at low energies should thus exceed that expected for simple blackbody emission (Ulmer 1994; Lyubarsky 2002). Photon splitting and merging will also be important in modifying the spectrum (Miller 1995; Thompson & Duncan 2001) at energies above around 30–50 keV.

At present, modeling of magnetar burst emission, and the atmospheric response of a magnetar to a flux at or exceeding the magnetic Eddington limit, is not sufficiently advanced to permit us to make firm predictions for spectral evolution (see Harding & Lai 2006 for an extended discussion of the difficulties inherent in modeling radiative transfer for magnetar bursts, which include the vastly disparate mean-free paths for the two polarization modes). We are therefore not yet in a position to say conclusively how, if PRE does occur and an underlying thermal region expands and cools, this would be reflected in the emergent spectrum. It seems logical, however, that we should expect at least a drop in the overall energy of emergent photons.

4. CONSEQUENCES OF IDENTIFYING PRE FROM A MAGNETAR

Detailed modeling of the type done for PRE X-ray bursts has not been done for magnetar bursts, so it is not possible to say conclusively whether the mechanism would work on the observed timescales.\(^10\) However, it certainly seems that it is plausible. The four conditions necessary for multi-peaked PRE bursts (Section 2) can be met within some of the envisaged emission scenarios (Section 3), particularly those involving radiation from an optically thick pair corona or trapped fireball into an open field line region. In this section, we will consider what could be learnt if we were able to identify a PRE episode during a magnetar burst.

4.1. Burst Emission Mechanism

As outlined in Section 3.1 the mechanism responsible for magnetar bursts is still not known. Two possible trigger mechanisms have been identified: crust rupturing (Thompson & Duncan 1995) and explosive magnetic reconnection (Lyutikov 2003). Both are capable of generating rise times that match the observations. In addition there needs to be some way of generating prolonged emission. In the crust fracture model, magnetic reconnection (Thompson & Duncan 1995) or QED instabilities (Heyl & Hernquist 2005) generate an optically thick $e^\pm$ plasma fireball. However, as outlined in Harding & Lai (2006), this model does not explain all aspects of the spectra, although it does explain the durations of the bursts by delaying energy release. What could generate the prolonged emission in the reconnection model is not entirely clear. A trapped fireball may be formed; alternatively the duration is related to the timescale over which repeated accelerations take place.

An identification of PRE would confirm that the emission was taking place in an optically thick region, hence ruling out purely magnetospheric emission mechanisms. The mechanism identified by Lyutikov (2003) could still be responsible for the initial burst trigger but would have to be augmented by some optically thick radiation storage mechanism. It would also confirm that emission is occurring via open field line regions (since the critical flux for closed field line regions would be much higher than the fluxes seen during most normal bursts).

4.2. Stellar Properties

The critical luminosity depends on magnetic field strength and the gravitational field of the star (Section 3.2). The flux at which a PRE episode occurs can therefore be used to confirm estimates of source distance and magnetic field strength obtained via other means (supernova remnant/globular cluster association and spin-down rate, for example).

Given trusted values of the source distance and magnetic field, one would then be able to use the critical flux to measure the gravitational redshift of the neutron star. With high enough time resolution one should be able to track changes in redshift as the photosphere lifts off, expands, and then touches back down. To obtain a constraint on mass and radius, one would need to measure redshift at take-off or touchdown. However, a measurement at maximum expansion would (in theory) tell you how far off the surface the photosphere had risen. Measuring magnetar redshifts would be extremely interesting, since in X-ray burst sources such estimates can be contaminated by the presence of the accretion disk (Galloway et al. 2008b).

5. THE 2008 AUGUST 24 BURST FROM SGR J0501+4516

SGR J0501+4516 was discovered with Swift when it became active on 2008 August 22 (Barthelmy et al. 2008; Enoto et al. 2009; Rea et al. 2009). The source emitted a series of very intense bursts during the next 13 days, triggering the Fermi Gamma-ray Burst Monitor (GBM) 26 times (Fishman et al. 2008; Kouveliotou et al. 2008). Subsequent Rossi X-Ray Timing Explorer (RXTE) observations revealed a period and a period derivative, enabling an estimate of the average dipole magnetic field of $1.9 \times 10^{14}$ G, placing the source among the magnetar candidates (Woods et al. 2008; Israel et al. 2008b). This is the first magnetar candidate seen from the Galactic anticenter direction, suggesting a location in the Perseus arm of our Galaxy at a distance of 1.95 $\pm$ 0.04 kpc (Xu et al. 2006). If this distance is confirmed, SGR J0501+4516 would be one of the two closest magnetar candidates to Earth, together with SGR J0418+5729, discovered in 2009 (van der Horst et al. 2009), which also likely resides in the Perseus arm (van der Horst et al. 2010).

On 2008 August 24, GBM recorded a very bright burst from SGR J0501+4516 with a pronounced double-peaked structure, and most importantly with the flux between peaks dropping almost to background levels (Figure 1). This peculiar burst light curve resembled those of X-ray bursts where PRE had been
observed (Lewin et al. 1993), motivating us to search for similar temporal and spectral signatures. One of the typical PRE X-ray burst characteristics is the drop of the flux to almost background level, after the initial pulse, followed by a second, more intense pulse. The gap between pulses appears above 6 keV in X-ray bursts and is longer for larger photon energies. Although in the August 24 SGR burst the first pulse is actually more intense than the second, we show in Figure 1 that there is an energy dependence of the gap size between pulses in the burst (see Figure 1 insets). The gap (from 125 to 225 ms after GBM trigger) is much more pronounced at higher energies.

Spectrally, the burst was observable between 8 and 300 keV and was so bright that it saturated the High Speed Science Data Bus of the GBM Data Processing Unit (Meegan et al. 2009). As a result, part of the light curve is artificially cut off and cannot be used for any reliable analysis (see the hashed area in Figure 1). We therefore performed spectral analysis outside the affected interval. We used the Time Tagged Event (TTE) data of NaI detectors 2 and 5 (Meegan et al. 2009), both with source angles to the detector normal of ∼46°, binned at 8 ms resolution. We fitted the full spectral range of the NaI detectors (8–1000 keV), excluding a few energy channels around the Iodine K edge at 23 keV, using the spectral analysis software RMFIT.11 We fitted various spectral models to the data: power law (PL), blackbody (BB), power law with an exponential cut off (Comptonized), optically thin thermal bremsstrahlung (OTTB), and combinations of PL and BB, and two BB functions. The best fits for both the time-integrated and time-resolved analysis were obtained with the Comptonized function. The time-integrated spectrum12 is best fit with an index of −0.22 ± 0.03 and $E_{\text{peak}} = 36.3$ ± 0.2 keV. The resulting photon and energy flux (8–300 keV) are 4.72 ± 0.05 and $1.1968 \times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$, respectively.

Our time-resolved analysis displays strong spectral evolution during the event, which is shown in Figure 2. We find that the $E_{\text{peak}}$ correlates strongly with the source flux when the burst is bright (photon flux >400 ph s$^{-1}$ cm$^{-2}$). This correlation breaks down at lower fluxes, where we even see an anti-correlation, in particular in the gap between the two bright pulses and in the tail of the burst. Furthermore, there is a correlation between the Comptonized power-law index and $E_{\text{peak}}$, with indices around 0 for the highest and ∼−1.5 for the lowest $E_{\text{peak}}$ values.

Since we were only able to analyze a part of the event, we cannot determine the peak or the total burst luminosity (or energy). We can, however, put a lower limit on the peak flux, namely, the one of the second pulse which has a lower peak flux than the saturated first pulse. The lower limit on the 8 ms peak energy flux (8–300 keV) is $(1.95 \pm 0.03) \times 10^{-4}$ erg s$^{-1}$ cm$^{-2}$.

Using Equation (20) we can estimate the critical magnetic Eddington flux as

$$F_{\text{crit}} \sim 2 \times 10^{-2} \text{erg cm}^{-2} \text{s}^{-1} \left(\frac{B}{10^{14} \text{G}}\right) \left(\frac{1 \text{keV}}{E_{\gamma}}\right) \times \left(\frac{1 \text{kpc}}{d}\right)^{2} \left(\frac{L_{\text{Edd}}}{2 \times 10^{58} \text{erg s}^{-1}}\right).$$

For $d = 1.95$ kpc and $B = 1.9 \times 10^{14}$ G, this yields $F_{\text{crit}} \sim 3 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$ for photon energies of 36 keV (the $E_{\text{peak}}$ value for the time-integrated burst spectrum). Inclusion of the gravitational redshift would lower the critical flux by 25%, to $2 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$. This is comparable to the lower limit on the peak flux we estimated for the August 24 event, and also with the 2 ms peak flux of $2 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$ measured by Konus–Wind (Golenetskii et al. 2008). This lends plausibility to the idea that we might be seeing an event that reaches the magnetic Eddington limit and then undergoes PRE.

We also investigated the light curve of the event versus the phase of the spin of the source, to try to identify whether the burst happens on an open or closed field line region (see below). The burst data were Earth barycentered and folded using the ephemeris obtained with RXTE. Pulse profiles constructed from RXTE and XMM–Newton data are shown in Figure 3. Full details of the spin and pulse profile analysis can be found in a companion paper (E. Göğüş et al. 2010, in preparation).

The burst happens during the rising part of the pulse profile below 10 keV, before the pulse maximum and before the pulse onset above 10 keV (dashed lines, Figure 3). If the model of Thompson & Duncan (1995) is accurate, pulse maximum corresponds to an open field line region, since the jets of radiation that form the main pulses escape along open field lines. This suggests that this particular burst occurs at the same rotational phase as an open field line region. This is consistent with the idea that you have to be on an open field line region in order to get radius expansion at reasonable luminosities (Section 3.2).

6. DISCUSSION

6.1. Models for Multi-peaked Magnetar Bursts

Multi-peaked magnetar bursts are a relatively common phenomenon. These are usually assumed to be superpositions of smaller bursts, due to the broad distribution of wait times between burst peaks (Göğüş et al. 2001). So is the 2008 August 24
Figure 3. Energy-resolved pulse profiles (0.3–40 keV) generated using RXTE and XMM–Newton data from 2008 August 22 to August 24. The closest RXTE pointing (2–40 keV) ends about 3000 s before the burst and the one after starts about 5000 s later. The XMM–Newton observations (0.3–2.0 keV) were taken a day before the burst. At higher energies than those shown the pulse profile is consistent with random fluctuations. The dashed lines indicate the phase interval within which the event took place.

If bursts that reach the magnetic Eddington limit are possible then we should consider the consequences for other sources and bursts. Table 1 shows the open field line magnetic Eddington limit predicted for other magnetars, for all magnetars with estimates of distance and magnetic field strength, for photon energies of 50 keV.\(^{13}\)

The last four sources listed in Table 1 (XTE J1810−197, 1E 1048.1−5937, AXP 2259+586, and CXO J164710.2−455216) have never shown bursts with peak fluxes as high as the predicted critical values (Gavriil et al. 2002, 2004; Kaspi et al. 2003; Woods et al. 2005; Israel et al. 2007). The other sources, however, have shown brighter bursts that have reached or exceeded the predicted critical flux.

SGR 0526−66, SGR 1627+41, SGR 1900+14, and 1E 1547.0−5408 (SGR J1550−5418) have all had regular (short) bursts with peak fluxes close to or exceeding the predicted limit (Golenetskii et al. 1987; Göğüş et al. 1999; Woods et al. 1999a, 1999b; Esposito et al. 2008; Mereghetti et al. 2009). A detailed study of those bursts that appear to exceed the critical limit is beyond the scope of this paper. For SGR 1806−20, however, which has a higher predicted critical luminosity due to its stronger field, the smaller bursts do not reach the limit (Göğüş et al. 2001).

The rarer intermediate bursts can also exceed the critical flux. SGR 1900+14 had three intermediate bursts in 2001 that exceeded the predicted critical flux (Kouveliotou et al. 2001; Ibrahim et al. 2001). The events on April 28 and August 29 show no multi-peaked structure in their light curves. However, the brightest event, on April 18, does have an unusual feature:

burst from SGR J0501+4516 really anything special? It was certainly rather unusual compared to most of these bursts. Having the flux dropping to near zero at all is rare (Woods & Thompson 2006). The profile—particularly the very rapid drop in emission before the secondary rise—is also odd. Most multi-peaked bursts, by contrast, have a longer decay time than rise time. It therefore seems reasonable to postulate that a different mechanism might be responsible for the double-peaked nature of this very bright burst.

### 6.2. Consequences for Other Magnetar Bursts

If bursts that reach the magnetic Eddington limit are possible then we should consider the consequences for other sources and bursts. Table 1 shows the open field line magnetic Eddington limit predicted for other magnetars, for all magnetars with estimates of distance and magnetic field strength, for photon energies of 50 keV.\(^{13}\)

The last four sources listed in Table 1 (XTE J1810−197, 1E 1048.1−5937, AXP 2259+586, and CXO J164710.2−455216) have never shown bursts with peak fluxes as high as the predicted critical values (Gavriil et al. 2002, 2004; Kaspi et al. 2003; Woods et al. 2005; Israel et al. 2007). The other sources, however, have shown brighter bursts that have reached or exceeded the predicted critical flux.

SGR 0526−66, SGR 1627+41, SGR 1900+14, and 1E 1547.0−5408 (SGR J1550−5418) have all had regular (short) bursts with peak fluxes close to or exceeding the predicted limit (Golenetskii et al. 1987; Göğüş et al. 1999; Woods et al. 1999a, 1999b; Esposito et al. 2008; Mereghetti et al. 2009). A detailed study of those bursts that appear to exceed the critical limit is beyond the scope of this paper. For SGR 1806−20, however, which has a higher predicted critical luminosity due to its stronger field, the smaller bursts do not reach the limit (Göğüş et al. 2001).

The rarer intermediate bursts can also exceed the critical flux. SGR 1900+14 had three intermediate bursts in 2001 that exceeded the predicted critical flux (Kouveliotou et al. 2001; Ibrahim et al. 2001). The events on April 28 and August 29 show no multi-peaked structure in their light curves. However, the brightest event, on April 18, does have an unusual feature:

### Table 1

| Source               | Distance (kpc)\(^{a}\) | Magnetic Field (×10\(^{14}\)G)\(^{b}\) | \(F_{\text{crit}}\) (erg cm\(^{-2}\) s\(^{-1}\)) |
|----------------------|------------------------|----------------------------------------|------------------------------------------|
| SGR 0501+4516        | 1.95 ± 0.04            | 2.0                                    | 3 × 10\(^{-4}\)                          |
| SGR 0526−66          | 50                     | 7.3                                    | 6 × 10\(^{-7}\)                          |
| SGR 1627−41          | 11 ± 0.3               | 2.2                                    | 4 × 10\(^{-6}\)                          |
| SGR 1806−20          | 15.1\(^{+1.3}_{-1.5}\) | 21                                     | 2 × 10\(^{-5}\)                          |
| SGR 1900+14          | 12−15                  | 6.4                                    | 7 × 10\(^{-6}\)                          |
| 1E 1547.0−5408\(^{d}\)| ~9                     | 2.2                                    | 5 × 10\(^{-6}\)                          |
| XTE J1810−197        | ~5                     | 1.7                                    | 1 × 10\(^{-5}\)                          |
| 1E 1048.1−5937       | 2.7 ± 1                | 4.2                                    | 1 × 10\(^{-4}\)                          |
| AXP 2259+586         | 3.0 ± 0.5              | 0.59                                   | 1 × 10\(^{-5}\)                          |
| CXO J164710.2−455216 | ~ 5                    | 1.6                                    | 1 × 10\(^{-5}\)                          |

Notes.

\(^{a}\) References for distances, in source order: Xu et al. 2006; Klose et al. 2004; Corbel et al. 1999; Corbel & Eikenberry 2004; Vrba et al. 2000; Camilo et al. 2007; Gotthelf et al. 2004; Gaensler et al. 2005a; Kothes et al. 2002; Clark et al. 2005. Note that some of these distances are rather uncertain, which will affect the estimated critical flux.

\(^{b}\) References for inferred magnetic fields, in source order: Woods et al. 2008; Kulkarni et al. 2003; Esposito et al. 2009; Mereghetti et al. 2005; Woods et al. 2002; Camilo et al. 2007; Gotthelf & Halpern 2005; Gavriil & Kaspi 2004; Gavriil & Kaspi 2002; Israel et al. 2007.

\(^{c}\) Using Equation (24) for 50 keV photons. Applying a GR correction would reduce this estimate by ≈25%.

\(^{d}\) Also designated as SGR J1550−5418.
at the end of the outburst, the flux drops suddenly to near zero before there is another peak (Guidorzi et al. 2004). The light curve of this event is very similar to the candidate PRE event from SGR 0501+4516. One of the bursts discussed by Israel et al. (2008a), on 2006 March 29, also reaches a peak flux of $1 \times 10^{-5}$ erg cm$^{-2}$ s$^{-1}$ and looks like a multi-peaked event. At least one of the blackbody spectral components that these authors fit expands and cools at the point where PRE would occur if this was happening: Israel et al. (2008a) comment on the fact that the flux is close to critical, but do not discuss this possible signature of PRE.

All three giant flares exceeded the predicted limit by orders of magnitude. For SGR 0526−66 both initial flare and the detected portion of the pulsating tail exceed the limit (Golenetskii et al. 1987). For SGR 1900+14, peak flux in the giant flare exceeded $3.4 \times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$ (Hurley et al. 1999). Flux would have dropped through the critical value as the light curve decayed, but no odd behavior is apparent in the light curve at this time. For SGR 1806−20, the precursor to the giant flare reached a flux of $3.2 \times 10^{-5}$ erg cm$^{-2}$ s$^{-1}$ (Boggs et al. 2007), very close to $F_{\text{crit}}$. The peak flux in the main burst was far above the critical level. The fluxes in the tail of the giant flare do drop through the critical flux, and it is interesting to note that the blackbody component (there is an additional spectral component as well) remains close to or lower than the critical flux (Palmer et al. 2005). It is possible that this component has reached the magnetic Eddington limit.

We note that mass ejection plays a significant role in giant flares, however, by blowing scattering material away from the neutron star surface (Gaensler et al. 2005b). Thompson & Duncan (1995) noted that the amount of energy released in the giant flares cannot all be trapped in the closed field region, and proposed that the main initial part of the burst comes out along the open field lines, driven by a wind from the pair plasma. In this case, PRE might not occur because the radiation pressure would be converted to kinetic energy that would drive the atmosphere to escape velocity. One extra condition for PRE to occur in magnetar bursts might be that strong winds do not form and that the atmosphere remains more or less static, or at least the motion does not reach escape velocity. In this case PRE in magnetar bursts might occur in a fairly small region of phase space between exceeding the magnetic Eddington limit and driving a strong wind.

7. CONCLUSIONS

We have examined the factors necessary for PRE to happen during thermonuclear X-ray bursts, and shown that they can also be met for some magnetar burst emission models. While additional conditions may also be necessary for PRE to occur during magnetar bursts, the possibility certainly seems plausible. An unambiguous identification of PRE in a magnetar burst, however, will require better burst spectral modeling taking into account the highly asymmetric emission and scattering environment around the star.

If magnetic PRE can be identified conclusively then it could prove to be a very useful tool. It would constrain, for example, the trigger and emission mechanisms for magnetar bursts. Identification of the magnetic Eddington limit also has potential as a new constraint of the equation of state, provided that the source distance and magnetic field strength can be measured by other means. We have argued that the 2008 August 24 burst from SGR 0501+4516 is a strong candidate for an open field line PRE burst. However, there are other events that reach or exceed the predicted critical fluxes in other magnetars. To test the consistency of our model these bursts must be given detailed consideration once better spectral and emission models are in place.

For magnetars PRE is certainly not inevitable at a given flux, as it appears to be for X-ray bursts. The occurrence of PRE will depend on whether emission occurs in open or closed field line regions, and on whether the initial burst has been so strong that scattering material has been blown away from the surface. PRE may however help to explain some of the extreme variability that we see in magnetar burst properties.

This publication is part of the GBM/Magnetar Key Project (NASA grant NNN07ZDA001-GLAST, PI: C. Kouveliotou). A.L.W. acknowledges support from a Netherlands Organization for Scientific Research (NWO) Vidi Fellowship, and would like to thank Maxim Lyutikov for discussions on magnetospheric triggers, and Duncan Galloway and Nevin Weinberg for discussions about PRE in X-ray bursts. A.J.v.d.H is supported by an appointment to the NASA Postdoctoral Program at the MSFC, administered by Oak Ridge Associated Universities through a contract with NASA. E.G. and Y.K. acknowledge EU FP6 Transfer of Knowledge Project “Astrophysics of Neutron Stars” (MTKD-CT-2006-042722). M.G.B. acknowledges support through NASA grant NNX10AC59A and NSF grant AST-0607651.

REFERENCES

Barthelmy, S. D., et al. 2008, ATel, 1676, 1
Bildsten, L. 1998, in NATO ASIC Proc. 515, The Many Faces of Neutron Stars., ed. R. Buchner, J. van Paradijs, & M. A. Alpar (Dordrecht: Kluwer), 419
Boggs, S. E., et al. 2007, ApJ, 661, 458
Brathwaite, J., & Nordlund, Å. 2006, A&A, 450, 1077
Brathwaite, J., & Spruit, H. C. 2006, A&A, 450, 1097
Camilo, F., Ransom, S. M., Halpern, J. P., & Reynolds, J. 2007, ApJ, 666, L93
Clark, J. S., Negueruela, I., Crowther, P. A., & Goodwin, S. P. 2005, A&A, 434, 949
Corbel, S., Chapuis, C., Dame, T. M., & Durochoux, P. 1999, ApJ, 526, L29
Corbel, S., & Eikenberry, S. S. 2004, A&A, 419, 191
Damen, E., Jansen, F., Penninx, W., Oosterbroek, T., van Paradijs, J., & Lewin, H. G. 1989, MNRAS, 237, 523
Damen, E., Magnier, E., Lewin, W. H. G., Tan, J., Penninx, W., & van Paradijs, J. 1990a, A&A, 237, 103
Damen, E., Wijers, R. A. M. J., van Paradijs, J., Penninx, W., Oosterbroek, T., Lewin, W. H. G., & Jansen, F. 1990b, A&A, 233, 121
Daugherty, J. K., & Harding, A. K. 1986, ApJ, 309, 362
Duncan, R. C. 1998, ApJ, 498, L45
Duncan, R. C. 2004, in Cosmic Explosions in Three Dimensions, ed. P. Höfsch, P. Kumar, & J. C. Wheeler (Cambridge: Cambridge Univ. Press), 285
Ebisuizaki, T., Hanawa, T., & Sugimoto, D. 1983, PASJ, 35, 17
Ebisuizaki, T., Sugimoto, D., & Hanawa, T. 1984, PASJ, 36, 551
Enoto, T., et al. 2009, ApJ, 693, L122
Esposito, P., et al. 2007, A&A, 476, 321
Esposito, P. 2008, MNRAS, 390, L34
Esposito, P., et al. 2009, MNRAS, L291
Feroci, M., Caliandro, G. A., Massaro, E., Mereghetti, S., & Woods, P. M. 2004, ApJ, 612, 408
Feroci, M., Hurley, K., Duncan, R. C., & Thompson, C. 2001, ApJ, 549, 1021
Fishman, G. J., et al. 2008, GRB Coordinates Network, 8139, 1
Gaensler, B. M., McClure-Griffiths, N. M., Oey, M. S., Haverkorn, M., Dickey, J. M., & Green, A. J. 2005a, ApJ, 620, L95
Gaensler, B. M., et al. 2005b, Nature, 434, 1104
Galloway, D. K., Muno, M. P., Hartman, J. M., Psaltis, D., & Chakrabarty, D. 2008a, ApJS, 179, 360
Galloway, D. K., Ozel, F., & Psaltis, D. 2008b, MNRAS, 387, 268
Galloway, D. K., Psaltis, D., Chakrabarty, D., & Muno, M. P. 2003, ApJ, 590, 995
Galloway, D. K., Psaltis, D., Muno, M. P., & Chakrabarty, D. 2006, ApJ, 639, 1033
Gavriil, F. P., & Kaspi, V. M. 2002, ApJ, 567, 1067
