A SUPRAMASSIVE MAGNETAR CENTRAL ENGINE FOR GRB 130603B

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ABSTRACT

We show that the peculiar early optical emission and, in particular, the X-ray afterglow emission of the short-duration burst GRB 130603B can be explained by continuous energy injection into the blastwave from a supramassive magnetar central engine. The observed energetics and temporal/spectral properties of the late infrared bump (i.e., the “kilonova”) are also found to be consistent with emission from the ejecta launched during a neutron star (NS)–NS merger and powered by a magnetar central engine. The isotropic-equivalent kinetic energies of both the gamma-ray burst (GRB) blastwave and the kilonova are approximately $E_k \sim 10^{51}$ erg, consistent with being powered by a near-isotropic magnetar wind. However, this relatively small value requires that most of the initial rotational energy of the magnetar (~a few $10^{52}$ erg) is carried away by gravitational wave radiation. Our results suggest that (1) the progenitor of GRB 130603B was a NS–NS binary system, the merger product of which would have been a supramassive NS that lasted for about $\sim 1000$ s; (2) the equation of state of the nuclear matter should be stiff enough to allow the survival of a long-lived supramassive NS; thus this suggested that the detection of the bright electromagnetic counterparts of gravitational wave triggers without short GRB associations is promising in the upcoming Advanced LIGO/VIRGO era.

Key words: gamma rays: general – radiation mechanisms: non-thermal

1. INTRODUCTION

Short-duration hard-spectrum gamma-ray bursts (GRBs), the durations of which are typically less than 2 s, have been widely speculated to be powered by mergers of two compact objects: either two neutron stars (NSs), NS–NS; or an NS and a black hole (BH), NS–BH (Eichler et al. 1989; Narayan et al. 1992). The tentative evidence for such progenitor models includes the host galaxy properties, the locations of the GRBS in the host galaxies, as well as the non-association of bright supernovae with short GRBs (Gehrels et al. 2005; Leibler et al. 2010). A “smoking-gun” signature of these events is the so-called kilonova, which is a supernova-like near-infrared/optical transient powered by the radioactive decay of heavy elements synthesized in the ejecta launched during the mergers (Li & Paczynski 1998; Kulkarni 2005; Rosswog 2005; Metzger et al. 2010) and sometimes also contributed to by a long-lived central engine (Kulkarni 2005; Yu et al. 2013). Such a signal had remained elusive until recently due to its faint and transient nature. At 15:49:14 UT on 2013 June 3, GRB 130603B (with a duration of $T_{90} = 0.18 \pm 0.02$ s in the 15–350 keV band) triggered the Burst Alert Telescope (BAT) onboard the Swift satellite. This burst is an archetypal short-hard GRB (de Ugarte Postigo et al. 2013) due to the following properties: (1) the BAT light curve did not show any “extended emission” down to ~0.005 count det$^{-1}$ s$^{-1}$ level; (2) spectral lag analysis revealed no significant lag between low and high energy photons; and (3) observations of the event by Konus/WIND gave a rest frame peak energy of $E_{\text{peak,rest}} = 895 \pm 135$ keV. A Hubble Space Telescope (HST) observation was made about one week after the trigger. It revealed a bright near-infrared source (Tanvir et al. 2013; Berger et al. 2013), which has been suggested to be consistent with the predictions of kilonova calculations (Kasen et al. 2013). This supports the compact star merger origin of this short GRB. Another possibility proposed by Jin et al. (2013), that the infrared bump may be attributed to the synchrotron radiation of a mildly relativistic blast wave, is disfavored by the non-detection of a simultaneous brightening in the radio band (Fong et al. 2013).

In this Letter, we constrain the central engine properties using both the early X-ray and $U$-band afterglow and the late infrared bump data. We argue that the data are consistent with a supramassive magnetar that undergoes significant gravitational wave energy loss during the early spin-down phase.

2. THE EARLY X-RAY AND $U$-BAND AFTERGLOW AND THE LATE INFRARED BUMP: SHEDDING LIGHT ON THE CENTRAL ENGINE

The X-ray Telescope on board Swift began to collect data from 43 s after the burst trigger. The most remarkable feature of the X-ray data is a shallow decline phase lasting ~1000 s (Figure 1, adapted from Evans et al. 2009). Swift’s Ultraviolet Optical Telescope (UVOT) began observing the burst approximately 62 s after the trigger. A faint source at the location of the afterglow was detected in all seven UVOT filters, but these emissions are so faint that a single $U$-band filter light curve was computed from the seven UVOT filters to improve the signal-to-noise ratio (de Ugarte Postigo et al. 2013). This is also presented in Figure 1 (data from de Ugarte Postigo et al. 2013 except that the upper limits are at a 3$\sigma$ confidence level). The early upper limits and later detections in the $U$-band suggest that the early $U$-band light curve should be flat or even rise with time. These features are difficult to interpret within the standard fireball afterglow model framework if the central engine energy injection is impulsive. This can be understood through the following. If the GRB central engine gives an impulsive energy injection, a shallowly decaying X-ray light curve and a slowly rising optical

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6 www.swift.ac.uk/xrt_curves/00557310/
We take a general energy injection law into the GRB blast wave from a long-lasting central engine long GRBs, which can be interpreted as an energy injection fast cooling model. The X-ray data are from Evans et al. (2009), while the u-band light curve is based on the data reported in de Ugarte Postigo et al. (2013). For a burst born in an interstellar matter-like circumstellar medium, we have $F_{\nu} \propto t^{0.5}$, which gives $\nu_{c} \approx 10^{16}$ Hz (de Ugarte Postigo et al. 2013; Jin et al. 2013). Together with the 6.7 GHz flux $\sim 0.13$ mJy at $t \sim 0.37$ days, one has $\nu_{m} \approx 2 \times 10^{12}$ Hz and the maximum specific flux $F_{\nu_{m}} \approx 0.8$ mJy (see also Fong et al. 2013). For a burst born in an interstellar matter-like circumstellar medium, we have $\nu_{c} \propto t^{-1/2}$ and $\nu_{m} \propto t^{-3/2}$ (Sari et al. 1998). Therefore at $t \sim 0.01$ days we have $\nu_{c} \approx 6 \times 10^{10}$ Hz and $\nu_{m} \approx 6 \times 10^{14}$ Hz, which are far from what are required in the fast cooling model.

An X-ray shallow decline phase is commonly observed in Swift long GRBs, which can be interpreted as an energy injection into the GRB blast wave from a long-lasting central engine (Zhang et al. 2006). We take a general energy injection law $dE_{\text{inj}}/dt \propto t^{-q}$ for $t < t_{\text{end}} \sim 10^{3}$ s (Zhang et al. 2006; Dai & Lu 1998; Zhang & Mészáros 2001), which gives $v_{m} \propto t^{-(3q-2)/2}$, $v_{c} \propto t^{(q-2)/2}$, and $F_{\nu_{\text{max}}} \propto t^{q-4}$. Since at $t \sim t_{\text{end}}$, one has $v_{m} \approx 10^{15}$ Hz and $v_{c} \approx 6 \times 10^{16}$ Hz, the optical emission should increase with time as $F_{\nu_{m}} \propto t^{8-5q}/6$ while the X-ray (1.7 keV) emission decreases with time as $F_{\nu_{c}} \propto t^{(2-2q)/5}$. For $q \sim 0$ relevant for a spinning down magnetar due to magnetic dipole radiation, both the peculiar X-ray and optical emissions can be accounted for (Figure 1). Such a relatively long, steady energy injection with a roughly constant luminosity is difficult to fulfill in the NS–NS or NS–BH merger scenarios with a BH central engine. Simulations suggest that long-lasting emission may arise in these systems, but the accretion rate history is essentially defined by the accretion rate of fall-back materials, which typically satisfies $dE_{\text{inj}}/dt \propto t^{-5/3}$ (see Figure 3 of Rosswog 2007a, for both NS–NS merger and NS–BH merger scenarios) and is far from what is required in current afterglow modeling. If the magnitude of the viscosity is $\alpha \sim 0.1$ for prompt accretion and $\sim 10^{-4}$ for fall-back accretion, both the short prompt emission and the $t_{0}$-like long-lasting energy injection may be accounted for (Lee et al. 2009). It is, however, unclear how $\alpha$ can change so much.

We then turn to the possibility that a long-lived supramassive magnetar rather than a BH was promptly formed after the merger (e.g., Gao & Fan 2006; Fan & Xu 2006; Metzger et al. 2008; Bucciantini et al. 2012; Rowlinson et al. 2013; Zhang 2013). This is possible if the NS equation of state is stiff enough, and if the total mass of the two merging NSs is not large enough (e.g., Morrison et al. 2004; Giacomazzo & Perna 2013). Indeed, for a sufficiently stiff equation of state yielding $M_{\text{max}} \approx 2.2–2.3 M_{\odot}$, the merger of double NSs with a total gravitational mass $M_{\text{tot}} \sim 2.6 M_{\odot}$ (note that among the 10 NS binary systems identified so far, 5 have such a total mass) can produce a supramassive magnetar with $P_{0} \sim 1$ ms, which survives until a good fraction of its rotational energy has been lost via dipole radiation and gravitational wave radiation (see Fan et al. 2013, and references therein).

As already mentioned, at $t \sim 0.35$ days, the key parameters governing the synchrotron spectrum are $\nu_{c} \approx 10^{16}$ Hz, $v_{m} \approx 2 \times 10^{12}$ Hz, and $F_{\nu_{\text{max}}} \approx 0.8$ mJy. Adopting Equations (2)–(4) of Fan & Piran (2006), it is straightforward to show that

$$E_{k} \approx 1.5 \times 10^{51} \text{ erg } n_{-1}^{-1/5}, \quad \epsilon_{e} \approx 0.2 n_{-1}^{1/5}, \quad \epsilon_{B} \approx 0.04 n_{-1}^{-3/5},$$

where $E_{k}$ is the isotropic-equivalent kinetic energy of the ejecta and $\epsilon_{e}$ ($\epsilon_{B}$) is the fraction of shock energy given to the electrons (magnetic field). $n$ is the number density of the interstellar medium and has been normalized to $0.1$ cm$^{-3}$, and the energy distribution power law index of the shock electrons is taken as $p = 2.3$ based on the optical and X-ray spectral data (de Ugarte Postigo et al. 2013; Jin et al. 2013). Please note that we have inserted the Compton parameter $Y \approx \frac{1}{2} + \frac{4(v_{m}/\nu_{c})^{p-2/7} \epsilon_{e}/\epsilon_{B}}{2} \sim 1$ into Equation (4) of Fan & Piran (2006) to estimate the physical parameters governing $\nu_{c}$.

Interestingly these relations impose a tight constraint on the isotropic-equivalent kinetic energy of the ejecta, i.e., $E_{k} \approx 1.5 \times 10^{51}$ erg ($\epsilon_{B}/0.04)^{1/3}$. It is well known that $\epsilon_{B}$ is not expected to be considerably larger than $\sim 1/3$ (i.e., the equilibrium argument, for which the shock energy is equally shared among electrons, protons, and magnetic fields), we then have

$$E_{k} \lesssim 3 \times 10^{51} \text{ erg}.$$  

Our result is remarkably consistent with the independent modeling of the late X-ray data by Fong et al. (2013), in which $E_{k} < 1.7 \times 10^{51}$ erg was inferred.

We have thus shown analytically that the peculiar X-ray and optical data in the first $\sim 1000$ s strongly suggests the energy injection of the magnetar into the blast wave. On the other hand,

![Figure 1](http://astrophysicsjournal.org/letters/779/L25/4pp/2013December20.png)
the normally declining late radio, optical, and X-ray afterglow data impose a very tight constraint on the kinetic energy of the blast wave \( E_k \sim 10^{51} \text{ erg} \). The energy injection rate is thus required to be

\[
\frac{dE_{\text{inj}}}{dt'} \sim (1+z)E_k/t_{\text{end}} \sim 10^{48} \text{ erg s}^{-1}.
\]

It is intriguing to note that modeling of the infrared bump also gives a similar isotropic energy for the kilonova component. According to Tanvir et al. (2013), Berger et al. (2013) and our numerical results below, the data require \( V_{\text{kilonova}} \sim 0.1–0.3c \) and \( M_{\text{kilonova}} \sim 0.03–0.08 M_\odot \), which correspond to \( E_{\text{kilonova}} \sim 10^{51} \text{ erg} \), regardless of whether or not there is a magnetar central engine. The near constant isotropic-equivalent kinetic energy in the jet component and the kilonova component would require coincidence if the central engine is a BH, but would be a natural outcome if the central engine is a millisecond magnetar. We postulate that the magnetar collapses into a BH at \( t_{\text{end}} \sim 1000 \text{ s} \). Interestingly, Fong et al. (2013) suggested that the X-ray afterglow had an unexpected excess at \( t > 1 \text{ day} \), which may be attributed to the emission powered by fall-back accretion onto a central BH. Such a model is in agreement with our scenario.

### 3. Possible Gravitational Wave Losses

For a long-lived magnetar formed in an NS–NS merger, the initial rotation period is expected to be \( P_0 \sim 1 \text{ ms} \), and only for such a short spin period can the uniform rotation play an non-ignorable role in stabilizing the magnetar (see Fan et al. 2013 and references therein). The initial rotational energy of a supramassive magnetar is therefore expected to be a few \( \times 10^{52} \text{ erg} \), much larger than the inferred \( E_k \sim 10^{51} \text{ erg} \). Lacking a bright electromagnetic emission component, the missing energy has to be carried away by a non-electromagnetic component. There is no known mechanism to release this huge amount of energy via thermal neutrinos. Here we focus on the possibility that the energy is carried away via gravitational wave radiation.

A magnetar loses rotational energy through magnetic dipole radiation and gravitational wave radiation (Shapiro & Teukolsky 1983)

\[
-dE_{\text{rot}}/dt' = \pi^4 R_s^6 B_\perp^2 f^4/6c^3 + 32\pi^6 G I_{\perp}^2 \epsilon^2 f^6/5c^5,
\]

where \( t' \equiv t/(1+z) \), \( \epsilon = 2(I_{xx} - I_{yy})/(I_{xx} + I_{yy}) \) is the ellipticity in terms of the principal moments of inertia (i.e., \( f \)), \( R_s \) is the radius of the magnetar, \( B_\perp \) is the surface magnetic field strength at the pole, and \( f = 2/P \) (\( P \) is the rotation period in units of second). To lose a considerable amount of rotational energy of the supramassive magnetar in \( t_{\text{end}} \sim 10^3 \text{ s} \) mainly via gravitational wave radiation, the ellipticity should be

\[
\epsilon \approx 0.0034 \left( \frac{I}{10^{45^2} \text{ g cm}^2} \right)^{-1/2} \left( \frac{P_0}{1 \text{ ms}} \right)^2 \left( \frac{t_{\text{end}}}{10^3 \text{ s}} \right)^{-1/2}.
\]

Such an ellipticity is larger than the maximum elastic quadrupole deformation of a conventional NS. It may be accommodated by one of the following two possibilities. First, if the magnetar is not a normal NS but crystalline color-superconducting quark matter (Xu 2003; Johnson-McDaniel & Owen 2013), then such a large deformation is allowed. The quark star model, although speculative, is also helpful in solving the baryon pollution problem of GRBs (Dai & Lu 1998; Paczynski & Haensel 2005). Another possibility discussed in the literature is that the super-strong interior magnetic field of a magnetar could induce a sizable prolate deformation (Dall’Ossio et al. 2009; Mallick & Schramm 2013). Indeed, a recent study on the magnetic field slow decay of NSs suggested that the initial interior magnetic field of both soft gamma-ray repeaters and anomalous X-ray pulsars is \( \gtrsim 10^{16} \text{ G} \) (Dall’Ossio et al. 2012). In principle, for a magnetar rotating with \( P_0 \sim 1 \text{ ms} \), an initial interior magnetic field \( \sim 10^{17} \text{ G} \) is possible (Duncan & Thompson 1992). The interior field is likely dominated by the toroidal component \( B_t \) (in a recent calculation, Fujisawa et al. 2012 found that the volume-averaged poloidal component could be \( \sim 5B_t \)).

Adopting Equation (4) of Usov (1992), \( \epsilon \approx 0.004 \) for \( B_t \sim 5 \times 10^{16} \text{ G} \). The large required deformation would be possible if the strong toroidal magnetic field is stable (e.g., Braithwaite 2009).

The dipole radiation of the supramassive magnetar has a luminosity (Shapiro & Teukolsky 1983)

\[
L_{\text{dip}} \approx 2.5 \times 10^{48} \text{ erg s}^{-1} \left( \frac{R_s}{10^6 \text{ cm}} \right)^6 \times \left( \frac{B_\perp}{5 \times 10^{14} \text{ G}} \right)^2 \left( \frac{P_0}{1 \text{ ms}} \right)^{-4},
\]

where \( B_\perp = B_t \sin \alpha \) and \( \alpha \) is the angle between the rotation and dipole axes. One can see the required magnetar luminosity \( E_k/t_{\text{end}} \) can be reproduced with a reasonable \( B_\perp \sim 5 \times 10^{14} \text{ G} \). For magnetar energy loss dominated by gravitational wave radiation, the energy injection rate into the blast wave and the ejecta launched during the merger can be approximated as

\[
dE_{\text{inj}}/dt' \approx L_{\text{dip}}(1 + t'/\tau_{\text{GW}})^{-1},
\]

as long as the gravitational wave radiation luminosity is much larger than \( L_{\text{dip}} \), where \( \tau_{\text{GW}} \approx 680 \text{ s} (I/10^{45^2} \text{ g cm}^2)^{-1} (P_0/1 \text{ ms})^{3}(\epsilon/0.004)^{-2} \) is the spin-down timescale of the magnetar due to gravitational wave radiation. For \( t' \leq t_{\text{end}} \approx \tau_{\text{GW}} \), the term \( (1+t'/\tau_{\text{GW}})^{-1} \) is almost a constant (i.e., \( dE_{\text{inj}}/dt' \propto t^{-1/2} \)), so that \( q = 0 \) applied in the above analysis is justified. For \( B_t < 10^{15} \text{ G} \), the spin-down of the magnetar by a neutrino-driven wind is likely unimportant (Thompson et al. 2004).

### 4. Numerical Modeling

Below we present our numerical results to fit the broadband data. With the code developed by Fan & Piran (2006) and Zhang et al. (2006), we take \( dE_{\text{inj}}/dt' = 1.6 \times 10^{48} \text{ erg s}^{-1} (1 + t'/1000 \text{ s})^{-1} \) for \( t' \leq t_{\text{end}} \approx 1000 \text{ s} \), and \( dE_{\text{inj}}/dt' = 0 \) otherwise, to model the afterglow light curves (Figure 1). By adopting the following forward shock physical parameters: \( \epsilon_e = 0.15, \epsilon_B = 0.03, p = 2.3, n = 0.15 \text{ cm}^{-3}, E_{k,0} = 2 \times 10^{50} \text{erg}, \) and \( \theta_j \approx 0.085 \), we show in Figure 1 that the X-ray and optical afterglow light curves up to \( \sim 1 \text{ day} \) can be reasonably reproduced. In contrast, the constant energy model (Figure 2 of Fong et al. 2013) over-predicts the X-ray flux early on. Our fit to the radio afterglow is somewhat poor (see Fong et al. 2013), possibly due to radio scintillation (Goodman 1997). Here \( E_{k,0} \) is the initial kinetic energy of the GRB ejecta and \( \theta_j \) is the half-opening angle of the GRB ejecta. These shock parameters are consistent with those found in Fong et al. (2013).
The magnetar wind is essentially mildly anisotropic. The wide-beam wind must run into the merger ejecta. Such an energy injection could lead the merger ejecta to have a mildly relativistic speed (Fan & Xu 2006; Zhang 2013; Gao et al. 2013) and/or to produce a bright “mergernova” (Yu et al. 2013; Kulkarni 2005). Adapting the same isotropic-equivalent rate of energy injection from the magnetar found in modeling the GRB afterglow, we fit the kilonova data using the method delineated in Yu et al. (2013), where the dynamical evolution of the merger ejecta is taken into account. The near-infrared data can be reproduced well given an ejecta mass of $M_{ej} \sim 0.02 M_\odot$, an initial velocity for the ejecta of $v_{ej,i} = 0.2c$, a magnetar collapsing time $t_{m,c} \sim 1000$ s, and an effective constant opacity $\kappa_e = 10^2$ g cm$^{-2}$. Here the adopted opacity is much higher than the typical one associated with electron scattering, because the bound–bound, bound–free, and free–free transitions of ions could provide more important contributions to opacity (e.g., Kasen et al. 2013; Tanaka & Hotokezaka 2013). The required ejecta mass is at the high end of simulated ejecta masses (Hotokezaka et al. 2013) for NS–NS mergers. The kilonova outflow is accelerated to a terminal velocity $v_{k,n} = 0.36c$, and its total kinetic energy is $\sim 10^{51}$ erg.

5. DISCUSSION

We have shown that an energy injection from a supramassive magnetar central engine can reproduce the early ($t \lesssim 10^3$ s) X-ray and optical afterglow data of the short GRB 130603B. The inferred isotropic-equivalent kinetic energies of both the afterglow and the kilonova are both $\sim 10^{51}$ erg. This is consistent with energy injection from a near-isotropic millisecond magnetar. The relatively small value of the energy budget requires that most of the energy is carried away via non-electromagnetic signals, and we argue that this is due to gravitational wave radiation with large deformation of the magnetar. The proposed Einstein Telescope may be able to detect the required gravitational wave radiation signal, if the source is within a distance of $\sim 100$ Mpc (Fan et al. 2013).

The strong evidence for a supramassive magnetar central engine from a NS–NS merger event suggests optimistic prospects for detecting the electromagnetic counterparts of gravitational wave triggers in the upcoming Advanced LIGO/VIRGO era. Since the magnetar wind is essentially isotropic, a bright early multi-wavelength afterglow is expected from gravitational wave triggers even without an associated short GRB (Zhang 2013; Gao et al. 2013; Yue et al. 2013), which can be readily detected by wide field X-ray and optical cameras.

Although the supramassive magnetar model has been widely adopted to interpret short GRB data, how a short GRB is produced by such a central engine is still an open question. One possibility is that the initial nascent NS rotates differentially and the magnetic braking and viscosity combine to drive the star to uniform rotation within a timescale $t_{diff} \sim 0.1–1$ s, if the surface magnetic field strength of the star reaches $10^{14}-10^{15}$ G (Shapiro 2000; Gao & Fan 2006). The magnetic activity of the differentially rotating NS may be able to drive short but energetic gamma-ray outbursts and thus account for the short GRB prompt emission (Rosswog 2007b). In the more speculative strange quark star scenario, phase transition from neutron matter to strange quark matter may proceed in a short period of time, and the released energy may power a short GRB. Alternatively, accretion of the disk material onto the strange quark star may also power a short GRB. In any case, a smoking-gun signature for the magnetar central engine for short GRBs may be retrieved from future gravitational wave data.

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