BRIGHT SUPERNOVAE FROM MAGNETAR BIRTH

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ABSTRACT

Following an initial explosion that might be launched either by magnetic interactions or neutrinos, a rotating magnetar radiating according to the classic dipole formula could power a very luminous supernova. While some $^{56}\text{Ni}$ might be produced in the initial explosion, the peak of the light curve in a Type I supernova would not be directly related to its mass. In fact, the peak luminosity would be most sensitive to the dipole field strength of the magnetar. The tail of the light curve could resemble radioactive decay for some time but, assuming complete trapping of the pulsar emission, would eventually be brighter. Depending on the initial explosion energy, both high and moderate velocities could accompany a very luminous light curve.

Key words: hydrodynamics – shock waves – supernovae: general – turbulence

1. INTRODUCTION

The role of rotation in powering the explosion of supernovae has long been debated (e.g., Hoyle 1946; LeBlanc & Wilson 1970; Ostriker & Gunn 1971; Akiyama et al. 2003). Most recent work has focused on the possibility that a rotating neutron star could, by way of a magnetic interaction, be the energy source for exploding a massive star. While that issue is far from resolved and recent headway has been made in exploring these same stars using neutrino transport (Janka et al. 2007), it is certain that a large fraction of supernova explosions produce rotating neutron stars and that those neutron stars frequently have large magnetic fields. Magnetars are a class of neutron stars with field strengths $10^{14}$ to $10^{15}$ G and more (Mereghetti 2008). They may constitute 10% of the neutron star birthrate (Kouveliotou et al. 1998). It is likely that fast rotation in the collapsing iron core is responsible for creating the large magnetic field (Duncan & Thompson 1992), so it is reasonable to expect that the birth of rapidly rotating, highly magnetic neutron stars is commonplace.

It is also generally assumed that these rapidly rotating neutron stars are magnetically braked by dipole emission early on, accounting for the slow periods observed in anomalous X-ray pulsars and soft gamma-ray repeaters (Duncan & Thompson 1992; Kouveliotou et al. 1998). Since the initial rotational energy of such stars at birth must have been large and 1000 years later is still small, where did the difference go? Might it have been emitted in some observable form (Ostriker & Gunn 1971)?

As a rough approximation, assume that the neutron star radiates its rotational energy away at a rate given by the traditional dipole formula for pulsars. For a typical moment of inertia of $10^{35}$ g cm$^2$, the rotational energy of a neutron star with period, $P_{\text{ms}}$, in milliseconds is

$$E = \frac{1}{2} I \omega^2 \approx 2 \times 10^{52} P_{\text{ms}}^{-2} \text{ erg}. \quad (1)$$

The approximate energy loss for dipole radiation is given by the Larmor formula (e.g., Lang 1980)

$$\frac{dE}{dt} = \frac{2}{3} (BR^3 \sin \alpha)^2 \left(\frac{2\pi}{P}\right)^4 \approx 10^{49} B_{15}^2 P_{\text{ms}}^{-4} \text{ erg s}^{-1}. \quad (2)$$

Here, $B_{15}$ is the surface dipole field in $10^{15}$ G, $R \approx 10^6$ cm is the neutron star radius, and $\alpha$ is the inclination angle between the magnetic and rotational axes, taken arbitrarily to be $30^\circ$.

At face value, these simple formulae suggest large luminosities for magnetars during the first few weeks of their lives. For example, the magnetar in SGR 1627-41 is estimated to have a current spin-down luminosity of $\sim 4 \times 10^{34}$ erg s$^{-1}$ at an age of 2.2 kyr implying a magnetic field $B \sin \alpha \sim 2 \times 10^{14}$ G (Esposito et al. 2009). Extrapolated back to when the magnetar was 10 days old, Equation (2) implies a luminosity of $2 \times 10^{34}$ erg s$^{-1}$. Provided the initial rotation rate was rapid compared with its value at 10 days, this result is independent of the initial rotation rate.

Here, we explore the observational characteristics of Type Ib/c supernovae in which pulsars with magnetar-like characteristics have been embedded. The brightest supernovae actually come from neutron stars with fields that, for a magnetar, are relatively modest, $\sim 10^{14}$ G. Larger fields imply that most of the magnetar’s rotational energy is dissipated early on, adding to the kinetic energy and mixing, but not appreciably affecting the luminosity. These luminous magnetar-powered supernovae might easily be confused with other forms of “hypernovae” where the luminosity has a radioactive origin. This may lead to invoking exotic models such as pair instability to explain abundances of $^{56}\text{Ni}$ that cannot be created in ordinary supernovae.

Alternatively, the lack of such emission constrains the existence of any rapidly rotating magnetar. This could be an important constraint in the context of gamma-ray bursts where the possibility of a magnetar power source is currently debated.

2. A MODEL EXPLOSION

The presupernova model adopted for our first study is a $4.37 M_\odot$ Wolf-Rayet star derived from the evolution of single $35 M_\odot$ main sequence star (Woosley & Heger 2007). This is a typical mass for Type Ib supernovae (Enßn & Woosley 1988) and could also originate from a star of $15–20 M_\odot$ that lost its hydrogen envelope in a binary rather than to a wind. The relatively small helium core mass will also demonstrate the possibility of a very luminous supernova from a light progenitor. A heavier model is explored later. This star was exploded with a piston located at $1.89 M_\odot$, the base of the former oxygen burning shell where the entropy per baryon was $S/NAk = 4.0$. The piston was moved with a speed such as to impart a final
The kinetic energy of the explosion is 1.2 × 10^{51} \text{ erg} without the pulsar and 1.6 × 10^{51} \text{ erg} with it.

Ten seconds after the explosion, when all important nucleosynthesis had ceased and the shock wave was still about 0.5 \( M_\odot \) beneath the stellar surface, energy deposition from an assumed embedded magnetar was turned on. A magnetic field of 10^{14} \text{ G} and an initial rotation period of 4.5 ms were assumed, corresponding to a rotational kinetic energy of 10^{51} \text{ erg}. Energy from the magnetar was deposited in the inner 10 zones of the model at a rate given by Equation (2), and complete trapping was always assumed. The mass of these 10 zones was 0.14 \( M_\odot \). During the first few weeks, these zones are quite optically thick, and it is reasonable to assume that whatever the nature of the pulsar emission (wind, \( \gamma \)-rays, etc.), it would deposit interior to this region and thermalize. At later times, the heat rapidly diffuses out of this region, and until very late times, when \( \gamma \)-rays might escape, it seems reasonable to deposit the energy as heat. Similar approximations have been used in the past to represent the energy deposited from the decay of radioactive \( ^{56}\text{Ni} \) and \( ^{56}\text{Co} \) and have given good agreement with observations (e.g., Woosley et al. 1995). The initial luminosity of the assumed pulsar was 10^{45} \text{ erg} \text{s}^{-1} (Equation (2)) which declined to 10^{42} \text{ erg} \text{s}^{-1} after 5.9 × 10^{7} \text{ s}. After 2 × 10^{11} \text{ s} the rotation period was 1.0 s.

The resulting light curve is shown in Figure 2. At early times the effect of the magnetar was negligible. Later, some of the energy went into accelerating the ejecta to higher speeds and creating a “bubble” inside the supernova. Still later, the energy was mostly radiated away and, at late times, the supernova luminosity tracked Equation (2). The light curve peaked at 7.3 × 10^{43} \text{ erg} \text{s}^{-1} (about five typical Type Ia supernovae) at 37 days. At that time, the pulsar was depositing 7.5 × 10^{43} \text{ erg} \text{s}^{-1}. The rise time from 10^{45} \text{ erg} \text{s}^{-1} was 24 days.

Also of some interest is now the magnetar emission modifies the dynamics of the explosion. Without the pulsar, the explosion energy was 1.2 × 10^{51} \text{ erg}; with it, the explosion energy is increased to 1.6 × 10^{51} \text{ erg}. That is, about 40% of the magnetar energy went into kinetic energy of expansion, while the remainder went into radiation. This energy is consistent with that inferred from the analysis of several supernova remnants that show evidence of containing magnetars (Vink & Kuiper 2006). Energy was not deposited uniformly in the ejecta though. Because the pulsar was a central source of heating, its energy went into inflating a bubble of lower density material inside the supernova. The boundary of this bubble is a dense shell in which resides about a solar mass of the ejecta (Figure 3). Other calculations, not illustrated here, show that if one assumes a larger magnetar rotational energy or stronger magnetic field, the velocity and mass of this thin shell are increased.

In three dimensions, this shell is probably unstable and, rather than being ejected as a thin spherical shell, the ejecta are probably mixed. This will affect the light curve, perhaps making it rise at an earlier time, and the morphology of the supernova remnant, perhaps leading to a “hole” in the remnant (Vink & Kuiper 2006; Kriss et al. 1985). Multi-dimensional studies of the coupled radiation transport and hydrodynamics are needed and are feasible, but are postponed for now. This mixing will also have important implications for the spectrum, especially at late times.
shows the energy that would result from the decay of 0.3 of 56Ni though the effect of 56Ni decay was not included in the Figure 4.

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that of SN 1998bw which accompanied GRB 980425 (Patat et al. 2001). The long tails that in fact go like $t^{-2}$, parallel for some time that expected from the decay of 56Co and if the light curve for the first year was all one had to go by, one might easily confuse a pulsar-powered model for one powered by radioactivity. Since the explosion energy and mechanism is left unspecified here, one could invoke a much higher kinetic energy (accompanying the birth of the magnetar) and obtain spectra like that seen in SN 1998bw. The light curve at peak would then be powered by a combination of radioactivity and pulsar emission.

However, the luminosity of SN 1998bw at times later than one year (Sollerman et al. 2002) argues against such a hybrid model. By 1000 days after the explosion, the supernova had declined to $\sim 10^{38}$ erg s$^{-1}$, whereas a pulsar with field strength $5 \times 10^{14}$ G would still be radiating $2 \times 10^{40}$ erg s$^{-1}$. In fact, a strict application of Equation (2) would imply that the pulsar must have been born with a field strength in excess of $8 \times 10^{15}$ G in order to satisfy the observational limit at late times, but then the magnetar would contribute all of its rotational energy to the explosion and none to the light curve.

Of course Equation (2) is an approximation whose validity can be questioned, especially at early times, and the magnetic field strength and orientation need not be constant with time. Given the freedom to pick a field decay rate, the entire light curve could be fit, but this seems somewhat contrived. Fitting the late time light curve with a combination of 56Co and 57Ni decay seems, for now, more natural (Sollerman et al. 2002).

3. A HEAVIER PROGENITOR AND A STRONGER FIELD

The same magnetar in supernovae with different masses and kinetic energies will give supernovae with different properties. Consider first the effect of the same magnetar as in the previous section ($E_{\text{tot}} = 10^{51}$ erg, $B_{15} = 0.1$) embedded in a Type Ib supernova with mass 7.29 $M_\odot$. The presupernova star here was the remnant of a 60 $M_\odot$ main sequence star of solar metallicity, again taken from the study of Woosley & Heger (2007), and might be a representative if magnetars come from a population that is much heavier than ordinary supernovae (Muno et al. 2006). Of course the relation between presupernova (helium core) mass and main sequence mass is complicated by the effects of rotationally induced mixing, (metallicity dependent) mass loss, and binary membership, so 60 $M_\odot$ is a very rough estimate. The star was exploded, as before, with a piston at the base of the oxygen shell (1.59 $M_\odot$) and given a final kinetic energy of 1.2 $\times 10^{51}$ erg. Explosive nucleosynthesis produced 0.11 $M_\odot$ of 56Ni though the effect of 57Ni decay was not included in the plots shown.

Figure 2 already showed the resulting light curve. It is very nearly the same as for the lower mass Model. With its larger mass and similar kinetic energy, the supernova expands slower, but the emerging light is only slightly delayed and on the tail, the light curves are identical.

Figure 4 shows what happens if the magnetar is assumed to have a stronger magnetic field, $B_{15} = 0.5$ and 0.7. More of the rotational energy is deposited early on and contributes to the expansion rate. Consequently, the light curve at peak is fainter and declines more rapidly. Smaller initial rotation rates (2 $\times 10^{50}$ and 5 $\times 10^{50}$ erg corresponding to periods of 10 ms and 6.3 ms) were employed, but the answer is not very sensitive to that. The extra energy would just accelerate the ejecta. Since the resulting thin spherical shells are probably not physical, they are not considered here.

The light curves in Figure 4 resemble, superficially at least, that of SN 1987A whose light curve was identical. It is very luminous and long lasting and might be confused with those of pair-instability supernovae or circumstellar interaction. Indeed, Maeda et al. (2007) have suggested a pulsar as the possible source powering the second (principal) maximum of the light curve of SN 2005bf.

If magnetars are the central engine that powers the long-soft class of gamma-ray bursts (e.g., Woosley & Bloom 2006), then it is reasonable to expect that they may contribute to the light curves of the supernovae that accompany them. On the one hand, this might facilitate the magnetar paradigm because the production of the necessary large amount of 56Ni has proven problematic (Bucciantini et al. 2009). Having an alternate explanation that involves magnetar energy input would solve this problem. On the other hand, if a magnetar contribution to the light curve can be ruled out based on the spectrum and late time light curve, one must wonder how the magnetar is so effectively concealed. Is the rotational energy extracted with such high efficiency in the first few seconds that the magnetar forever afterward rotates slowly, or do rotating magnetars not emit according to the popular dipole formula during the first year?

Perhaps they do not. The absence of a pulsar contribution to the luminosity of typical supernovae is easy to understand. A pulsar born with a 14 ms period ($10^{30}$ erg), would only have a pulsar luminosity of $6 \times 10^{39}$ erg s$^{-1}$ during the time when it is bright. This is small compared with the $10^{42}$–10$^{43}$ erg s$^{-1}$ resulting from shock energy released by recombination (Type II supernova) or radioactivity (Type I supernova). But the extremely faint optical luminosity of SN 1987A, $< 8 \times 10^{37}$ erg s$^{-1}$, 17 years after its birth (Graves et al. 2005) is very difficult to reconcile with any model with a young active pulsar. While dust extinction could be considerable, the lack of a point source in SN 1987A remains a mystery.

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REFERENCES

Akiyama, S., Wheeler, J. C., Meier, D. L., & Lichtenstadt, I. 2003, ApJ, 584, 954

Bucciantini, N., Quataert, E., Metzger, B. D., Thompson, T. A., Arons, J., & Del Zanna, L. 2009, MNRAS, 396, 2038

Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9

Ensman, L. M., & Woosley, S. E. 1988, ApJ, 333, 754

Esposito, P., et al. 2009, MNRAS, 399, L44

Graves, G. J. M., et al. 2005, ApJ, 629, 944

Hoyle, F. 1946, MNRAS, 106, 343

Janka, H.-T., Langanke, K., Marek, A., Martínez-Pinedo, G., & Müller, B. 2007, Phys. Rep., 442, 38

Kouveliotou, C., et al. 1998, Nature, 393, 235

Kriss, G. A., Becker, R. H., Helfand, D. J., & Canizares, C. R. 1985, ApJ, 288, 703

Lang, K. R 1980, Astrophysical Formulae (Berlin: Springer)

LeBlanc, J. M., & Wilson, J. R. 1970, ApJ, 161, 541

Maeda, K., et al. 2007, ApJ, 666, 1069

Mereghetti, S. 2008, A&AR, 15, 225

Muno, M. P., et al. 2006, ApJ, 636, L41

Ostriker, J. P., & Gunn, J. E. 1971, ApJ, 164, L95

Patat, F., et al. 2001, ApJ, 555, 909

Sollerman, J., et al. 2002, A&A, 386, 944

Vink, J., & Kuiper, L. 2006, MNRAS, 370, L14

Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507

Woosley, S. E., & Heger, A. 2007, Phys. Rep., 442, 269

Woosley, S. E., Langer, N., & Weaver, T. A. 1995, ApJ, 448, 315