Letter to the Editor

A magnetar model for the hydrogen-rich super-luminous supernova iPTF14hls

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Abstract

Transient surveys have recently revealed the existence of H-rich super-luminous supernovae (SLSN; e.g., iPTF14hls, OGLE-SN14-073) that are characterized by an exceptionally high time-integrated bolometric luminosity, a sustained blue optical color, and Doppler-broadened H\textsc{i} lines at all times. Here, I investigate the effect that a magnetar (with an initial rotational energy of \(4 \times 10^{52}\) erg and field strength of \(7 \times 10^{13}\) G) would have on the properties of a typical Type II supernova (SN) ejecta (mass of \(13.35\ M_\odot\), kinetic energy of \(1.32 \times 10^{51}\) erg, \(0.077\ M_\odot\) of \(^{56}\text{Ni}\)) produced by the terminal explosion of an H-rich blue supergiant star. I present a non-local thermodynamic equilibrium time-dependent radiative transfer simulation of the resulting photometric and spectroscopic evolution from 1 d until 600 d after explosion. With the magnetar power, the model luminosity and brightness are enhanced, the ejecta is hotter and more ionized everywhere, and the spectrum formation region is much more extended. This magnetar-powered SN ejecta reproduces most of the observed properties of SLSN iPTF14hls, including the sustained brightness of \(-18\) mag in the \(R\) band, the blue optical color, and the broad H\textsc{i} lines for 600 d. The non-extreme magnetar properties, combined with the standard Type II SN ejecta properties, offer an interesting alternative to the pair-unstable super-massive star model recently proposed, which involves a highly energetic and super-massive ejecta. Hence, such Type II SLSNe may differ from standard Type II SNe exclusively through the influence of a magnetar.

Key words. radiative transfer – hydrodynamics – supernovae: general – stars: magnetars

1. Introduction

Super-luminous supernovae (SLSNe) owe their exceptional instantaneous and/or time-integrated luminosities to a non-standard source of energy and power. This power source may be interaction between a (standard-energy) ejecta with dense, massive, and slow-moving circumstellar material, leading to the formation of a heat engine (Kasen & Bildsten 2010). This engine is the high-energy counterpart to the collapse timescale, the outer shell recombines and the photosphere velocities). After a bolometric maximum is reached on a diffusion timescale, the outer shell recombines and the photosphere.
Table 1. Summary of the model properties.

| Model   | $R_*$ [M$_\odot$] | $M_{ej}$ [M$_\odot$] | $E_{kin}$ [erg] | $^{56}$Ni [M$_\odot$] | $E_{pm}$ [erg] | $B_{pm}$ [G] |
|---------|-------------------|----------------------|-----------------|----------------------|----------------|-------------|
| a4pm1   | 50                | 13.35                | 1.32(51)        | 0.077                | 4.0(50)        | 7.0(13)     |
| m15mlt3 | 501               | 12.52                | 1.34(51)        | 0.086                | ...            | ...         |
| R190NL  | 4044              | 164.1                | 33.2(51)        | 2.63                 | ...            | ...         |

Notes. The table includes the progenitor surface radius, the ejecta mass, its kinetic energy, and initial $^{56}$Ni mass, as well as the magnetar properties (for model a4pm1).

where $c$ is the speed of light. I used $E_{pm} = 4 \times 10^{50}$ erg, $B_{pm} = 7 \times 10^{13}$ G, $I_{pm} = 10^{45}$ g cm$^2$. I injected a magnetar power given by

$$E_{pm} = \frac{6I_{pm}c^3}{B_{pm}^2 R_{pm}^6 \rho_{pm}^{-1}}$$

and $R_{pm} = 10^6$ cm (see Kasen & Bildsten 2010 for details). This magnetar has a spin-down timescale of 478 d. The energy released during the first day, which was neglected, is only 0.2% of the total magnetar energy. Furthermore, I assumed that all the energy liberated by the magnetar is channelled into ejecta internal energy (and eventually radiation); CMFGEN does not treat this. This is a good approximation for this weakly magnetized object (see also Dessart & Audit 2018). In CMFGEN, I treated the magnetar power in the same way as radioactive decay. Energy was injected as 1 keV electrons for which the degradation spectrum was computed. The contribution to heat and non-thermal excitation/ionization was then calculated explicitly.

To mimic the effect of fluid instabilities (Chen et al. 2016; Suzuki & Maeda 2017), the magnetar energy was deposited over a range of ejecta velocities. The deposition profile follows $\rho$ for $V \leq V_0$, and $\rho \exp\left((-V/(V-V_0)/dV)^2\right)$ for $V > V_0$. Model a4pm1 used $V_0 = 4000$ km s$^{-1}$ and $dV = 2000$ km s$^{-1}$.

3. Results

The top panel of Fig. 1 shows the bolometric light curves for the model set. The magnetar-powered SN is super-luminous, intermediate during the first year between the standard SN II-P and R190NL, and the pair-instability Type II SN model R190NL (Dessart et al. 2013b), which I then compare with the photometric and spectroscopic observations of iPTF14hls. Following A17, I adopt an explosion date $MJD = 56922.53$, a distance of 156 Mpc, a redshift of 0.0344, and I assume zero reddening. Section 4 concludes the Letter.
model m15mlt3 and the PISN model R190NL. It is the brightest of all three at late times. Model a4pm1 is faint early on because of the small progenitor radius. After \( \sim 50 \) d, it closely follows the iPTF14hls \( R \)-band light curve (bottom panel of Fig. 1). The adopted magnetar power is continuous and monotonic, therefore it cannot explain the observed \( R \)-band fluctuations of \( \sim 0.5 \) mag in iPTF14hls. These might indicate the intrinsic variability of the proto-magnetar. However, the rotation energy of \( 4 \times 10^{50} \) erg and the magnetic strength of \( 7 \times 10^{13} \) G in model a4pm1 yield a suitable match to the overall brightness and slow fading. The discrepancy at early times would be reduced if an extended progenitor were used. A broader energy deposition profile or asymmetry might resolve this discrepancy.

Figure 2 shows that over the time span 100–600 d after explosion, model a4pm1 has a weakly evolving and blue optical color, in contrast to the non-monotonic and strongly varying color evolution of models m15mlt3 and R190NL. Up to \( \sim 50 \) d, model a4pm1 is redder because the progenitor is compact rather than extended. This additional cooling from expansion is superseded after \( \sim 50 \) d by the slowly decreasing magnetar power. Model a4pm1 closely follows the \( V - I \) color of iPTF14hls, which is fixed at about 0.2 mag (A17).

Up to the time of maximum, this bolometric and color evolution reflects the evolution of the ejecta properties and of the photosphere, taken as the location where the inward-integrated electron scattering optical depth \( \tau_{es} \) equals 2/3 (Fig. 3). In model a4pm1, the initial evolution is very rapid, as obtained in models of blue supergiant star explosions and inferred from the observations of SN 1987A (Dessart & Hillier 2010). At the photosphere, the velocity (temperature) drops from 17 300 km s\(^{-1}\) at 1.21 \( \times \) 10\(^5\) to 1.33 at 600 d, which is close to the value of 4.92 that would result for constant ionization (A17). This means that in model a4pm1, the inhibition of recombination maintains the ejecta in an optically thick state to electron scattering for more than 600 d. Lines of \( \text{H} \text{I} \) or \( \text{Ca} \text{II} \) will remain optically thick (and therefore broad) for even longer. Between 75% and 100% of the magnetar power goes into heat. Whatever remains is shared equally between excitation and ionization. In model a4pm1, non-thermal effects are inhibited by the partial ejecta ionization.

The photospheric evolution is not a reliable guide to understand the SN luminosity after maximum. The large photospheric radii combined with the large ejecta ionization cause a flux dilution by electron scattering. The SN spectrum may resemble a blackbody (A17), but at best diluted, with a thermalization radius much smaller than the photospheric radius (Eastman et al. 1996; Dessart & Hillier 2005). For example, at 250 d, \( \tau_{es} \) is 7.4, which is too small to ensure thermalization. Instead, the conditions are nebular and the SN luminosity equals the magnetar power (Fig. 1).

Model a4pm1 shows very little spectral evolution from 104 d (date of the first spectrum taken for iPTF14hls) until 600 d (Fig. 4), which in part reflects the fixed photospheric conditions (velocity and temperature) after 10 d (Fig. 3). The spectra show the \( \text{H} \alpha \) Balmer lines, \( \text{Fe} \text{II} \) lines around 5000 \( \AA \), and the \( \text{Ca} \text{II} \) triplet around 8500 \( \AA \). After about 300 d, the triplet is seen only in emission. \( \text{H} \alpha \) stays broad at all times, and the \( \text{Ca} \text{II} \) doublet 7300 \( \AA \) strengthens as the conditions in the ejecta become more nebular. Throughout this evolution, there is little sign of the blanketing that would appear in the optical range if the ejecta ionization dropped. The spectral evolution of model a4pm1 is similar to that observed for SLSN iPTF14hls, with a few discrepancies. The model underestimates the width of the \( \text{H} \alpha \) absorption trough, although it matches the emission width at all times. Adopting a broader energy-deposition profile would produce broader line absorptions (in a similar way to adopting a stronger \( ^{56} \text{Ni} \) mixing in Type Ibc SNe; Dessart et al. 2012a).

The model also underestimates the strength of the \( \text{Ca} \text{II} \) emission at late times. The feature at 5900 \( \AA \) is not predicted.
by the model. This is probably Na I D, because if it were He I \(\lambda 5875\) Å, one would expect a few other optical He I lines, which are not seen. Hence, our model may overestimate the ionization. Allowing for clumping might solve this issue (Jerkstrand et al. 2017).

The Doppler velocity at maximum absorption in H I or Fe II lines is high, greater than the photospheric velocity, and does not change much after about 50 d – the fast outer ejecta material is scanned at early times, before the magnetar has influenced the photosphere (Fig. 5). These lines eventually form over a large volume that extends far above the photosphere. These properties hold qualitatively even in standard Type II SNe.

4. Conclusion

In this Letter, I have presented the first non-LTE time-dependent radiative transfer simulation of a Type II SN influenced by a magnetar. I have shown that a magnetar-powered SN ejecta from a radiative transfer simulation of a Type II SN influenced by a magnetar. I have shown that a magnetar-powered SN ejecta from a Type II SN is a super-massive ejecta. As discussed in Dessart & Audit (2018), a similar magnetar-powered SN, with a standard ejecta mass and energy, may be at the origin of the SLSN OGLE-SN14-073, for which Terreran et al. (2017) also invoked a highly energetic and super-massive ejecta.

Fig. 4. Comparison of the multi-epoch spectra of SLSN iPTF14hls with model a4pm1. Times and wavelengths are given in the rest frame. Model and observations are renormalized at 6800 Å. For each date, I give the R-band magnitude offset (see also Fig. 1).

Fig. 5. Evolution of the Doppler velocity at maximum absorption in various lines and the photospheric velocity in model a4pm1. I overplot the corresponding values for H\(\alpha\) in iPTF14hls. The x-axis uses a logarithmic scale. The horizontal line gives the ejecta velocity \(\sqrt{2E_{\text{kin}}/M_{\text{ej}}}\).

Hence, Type II SLSNe that at all times show a blue color, broad H I spectral lines, and a weaker-than-average blanketing may differ from standard Type II SNe primarily through the influence of a magnetar.

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