Superluminous Supernovae Powered by Magnetars

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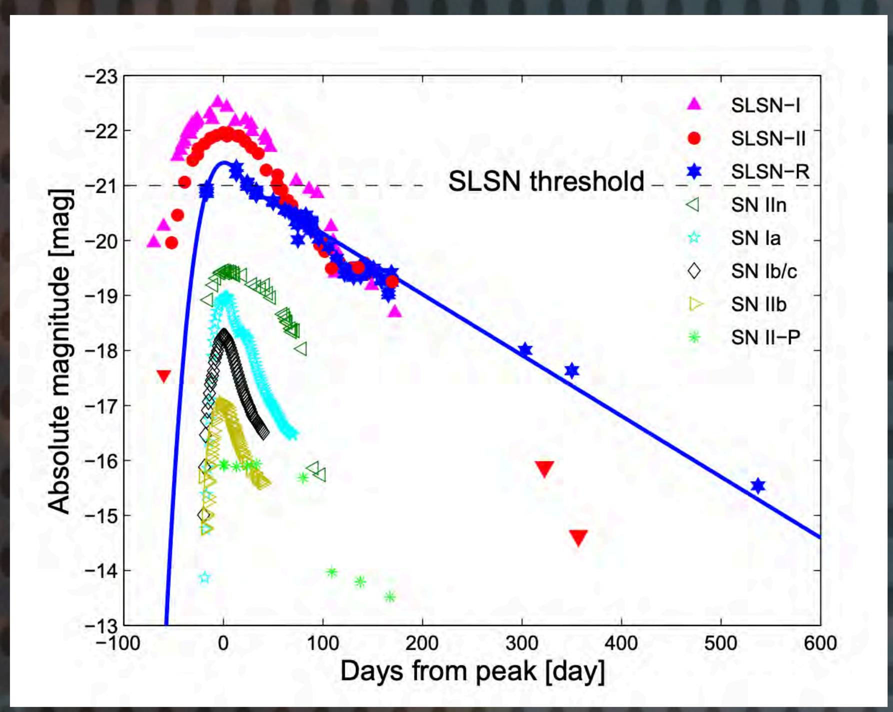
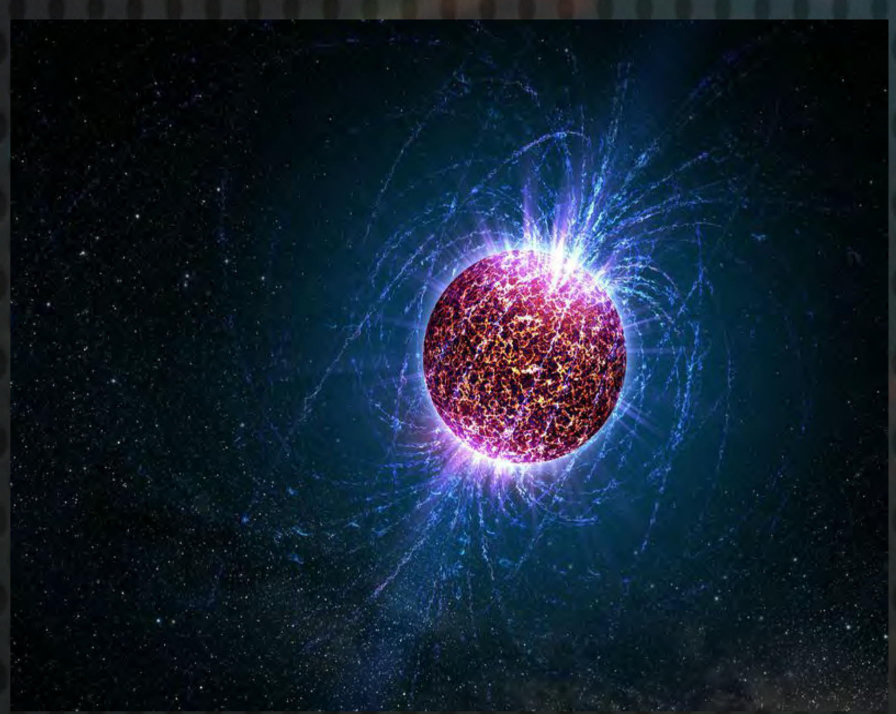
Introduction

SLSNe are a class of stellar explosions originally defined to have an absolute magnitude of M < -21 or $\sim 1e44\, erg/s$ at peak. There have been two distinct subcategories observed. These events are now categorized by their unique spectra as there is evidence to show that these events occur across a larger range of Magnitudes. Their lightcurves are shown in the figure below from Gal-Yam, M. 2012..



Magnetars

Strongly magnetized, rapidly rotating neutron stars known as magnetars are contenders for the central engines of hydrogen-poor superluminous supernovae (SLSNe). Approximately 10% of newly born neutron stars have dipole magnetic field of approximately $10^{14}-10^{15}\ G$. This is estimated through previous studies of gamma-ray repeaters and anomalous X-ray pulsars. These magnetars have periods of 5-12s approximately 1000-10,000 years after birth. This implies magnetars would have periods at birth of approximately 1-30ms. (Kasen & Bildsten 2010)



Magnetar Engine Model

There are a number of different models which describe the conditions that may cause these tremendous events. In this project the focus is on the millisecond magnetar engine model. This model predicts the formation and subsequent spin down of a magnetar as the center of the explosion. To probe the system we examine its internal energy which is given by the first law of thermodynamics:

$$\frac{\partial E_{int}}{\partial t} = -P\frac{\partial V}{\partial t} + L_m(t) - L_t(t)$$

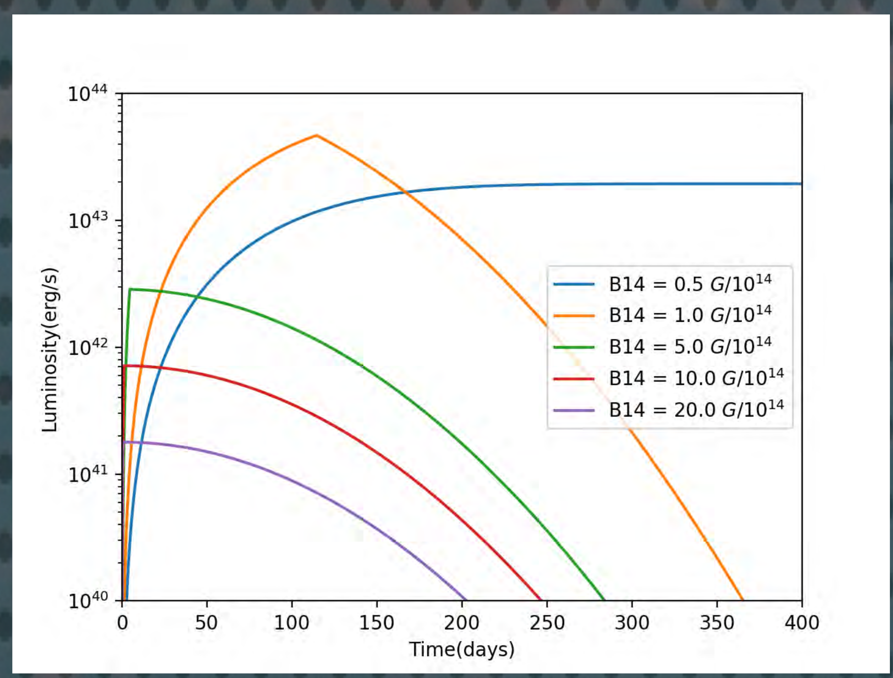
Analytic Model

Assumptions:

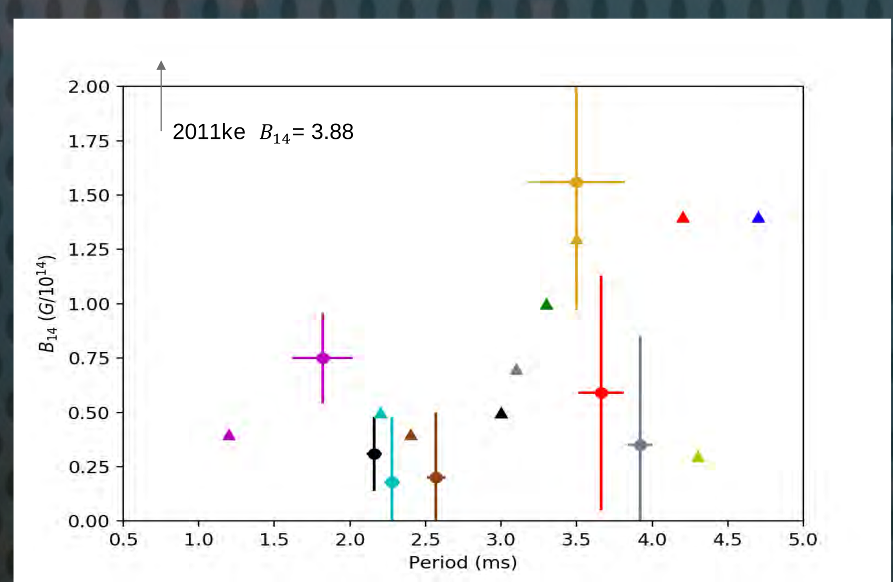
1. radiation pressure dominates such that: $P = \frac{E_{int}}{3V}$
2. Expansion is homogenous such that: $V \propto t^3$
3. Magnetar injects a constant luminosity over a time t_p then shuts off: $L_m = E_p/t_p$
4. The radiated Luminosity L_t can be estimated by the diffusion equation: $L_t = \frac{E_{int}t}{t_d^2}$

Where t_d is the effective diffusion timescale and t_p is the effective spin down timescale. Under these assumptions the expression for the internal energy can be solved yielding:

$$L(t) = \begin{cases} \frac{E_p}{t_p}\left(1-\exp\left(-\frac{t^2}{2{t_d}^2}\right)\right), t < t_p \\ \frac{E_p}{t_p}\exp\left(-\frac{t^2}{2{t_d}^2}\right)\left(\exp\left(-\frac{{t_p}^2}{2{t_d}^2}\right)-1\right), t > t_p \end{cases}$$



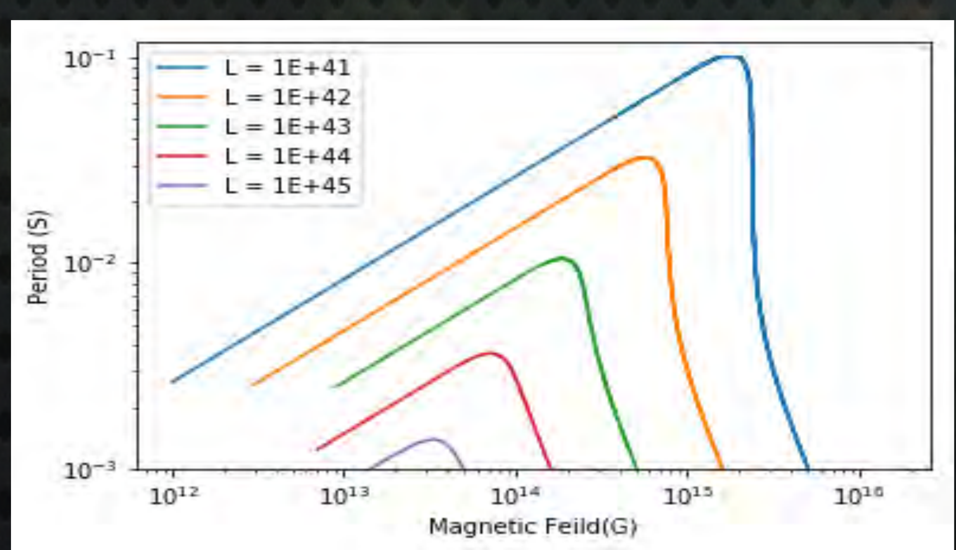
This model was fit to observation data from a number of type one SLSNe and yielded the following. Our results were compared to that of Nicholl, M. et al. 2017:



Peak Luminosity

From the previous analytic solution the peak luminosity is given by:

$$L_{peak} = \frac{E_p}{t_p}\left(1-\exp\left(-\frac{{t_p}^2}{2{t_d}^2}\right)\right)$$



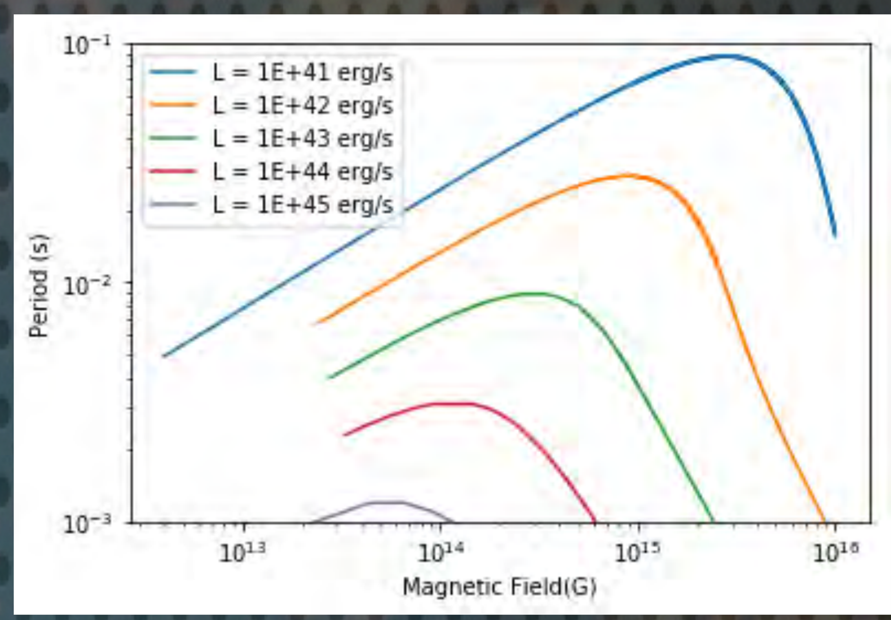
In reality however the energy input from the magnetar persists for $t > t_p$ and it is given by the spin down formula:

$$L_m = \frac{E_p}{t_p}\frac{1-l}{(1+{}^{t}/_{t_p})^l}$$

No simple analytic solution exists for the light curve for a general L_m. An approximate solution can be derived by setting $L_t = 0$ as radiative losses are minimal for $t < t_d$.
Then the resulting internal energy can be evaluated at t_d to estimate the peak Luminosity. This yields the following for magnetic dipole spin-down:

$$L_{peak} = \frac{fE_p t_p}{{t_d}^2}\left(\ln\left(1+\frac{t_d}{t_p}\right)+\frac{t_d}{t_p+t_d}\right)$$

The expression above has no analytic solution for period as a function of peak luminosity and magnetic field however it could be solved numerically. The figure below show the period as a function of magnetic field and peak luminosity. Each curve represents a line of constant peak luminosity.



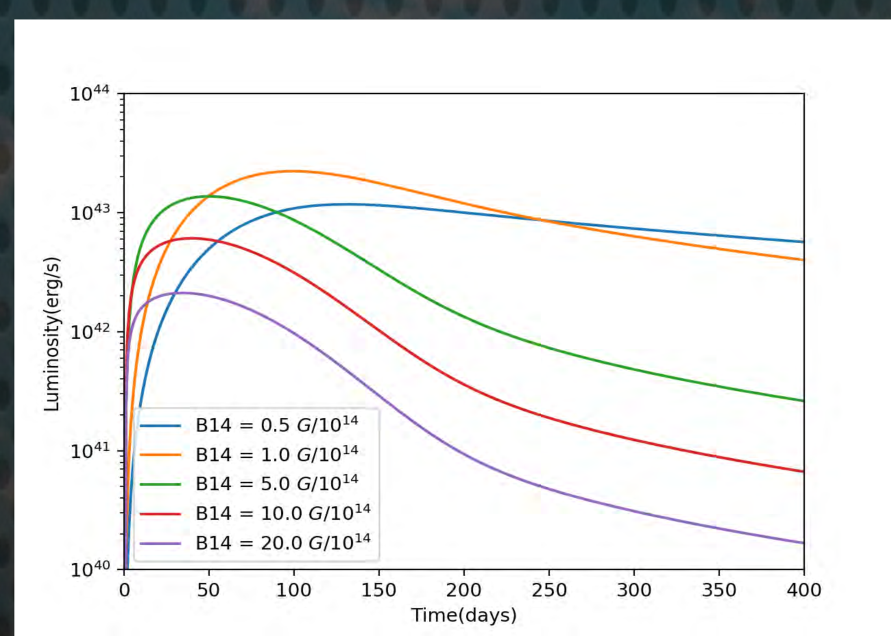
Numerical Simulation

Assumptions:

1. Radiated Luminosity is given by the radiation diffusion approximation: $L = -\frac{4\pi r^2 \lambda c a}{3}\frac{dT^4(x,t)}{dr}$
2. Energy input from magnetar is give by dipole spin down formula: $L_m = \frac{E_p}{t_p}\frac{1-l}{(1+{}^{t}/_{t_p})^l}$

Under these assumptions the expression for the internal energy can be solved by means of separation of variables yielding:

$$L(t) = \frac{2E_p}{t_p}e^{-\left(\frac{t}{t_d}+\frac{R_0 t}{v t_d^2}\right)}\int_0^{x'} e^{\left(z^2+\frac{R_0 z}{v t_d}\right)}\left(\frac{R_0}{v t_d^2}+z\right)\frac{dz}{(1+yz)^2}$$



Conclusion

The results of analytic model fit observations well away from extreme values of period and B_{14} and predicts well behavior about maximum, for small $B_{14} \leq 5\frac{G}{10^{14}}$ and for periods $\geq 1ms$. As expected, away from the maximum this model drops off too quickly due energy input being turned off. Finally, the observed degeneracy in solutions of the analytic model can be understood in conjunction with the numerical model and the equations of constant luminosity.