Hydrodynamic modeling of SLSNe
Application to the unprecedentedly bright ASASSN-15lh

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We use our radiation hydrodynamic code in order to simulate magnetar powered Superluminous Supernovae (SLSNe). As previously proposed, we assume that the central rapidly rotating magnetar deposits all its rotational energy into the ejecta. The magnetar luminosity and spin-down timescale are adopted as the free parameters of the model. For the case of ASASSN-15lh (SN 2015L), which has been claimed as the most luminous SN ever discovered, we have found physically plausible magnetar parameters can reproduce the overall shape of the bolometric light curve (LC) provided the progenitor mass is relatively large (i.e. an ejected mass of $\approx 6 M_\odot$). We note the ejecta hydrodynamics of this event is dominated by the magnetar input. This and other numerical experiments lead us to conclude that the hydrodynamic modeling is necessary in order to derive the properties of magnetars driven SLSNe and to characterize their stellar progenitors.

Hydrodynamic modeling

SLSNe show a factor 10 to 100 times brighter than normal core-collapse supernovae (Quimby etc) One possible mechanism invoked to explain them is that a magnetar is formed by the collapse of a massive star. Although some progress in the area were recently reported, rather important aspects of the scenario are still unclear. See e.g. Moriya et al (2016) discussion.

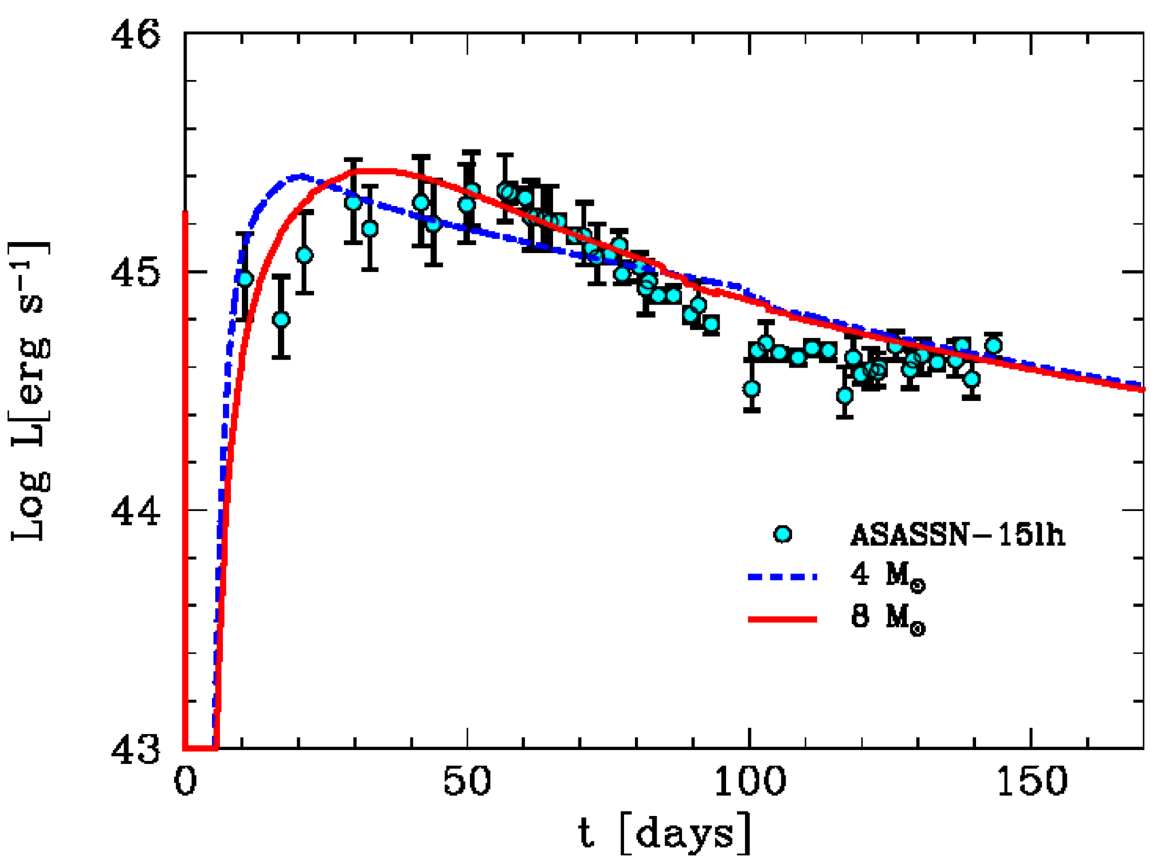
Magnetar models have been proposed for the extreme case of ASASSN-15lh. However, the analysis was based on simplistic assumptions that neglected the dynamic effects on the ejecta. Here we sumarize on our study (reported in Bersten et al. 2016) using hydrodynamic calculations of SLSNe which incorporate the dynamical effect of the newly born magnetar energy injection. This energy is assumed to be fully trapped, crucially converted in thermal energy of the ejecta even if the ejecta is thin to optical photons.

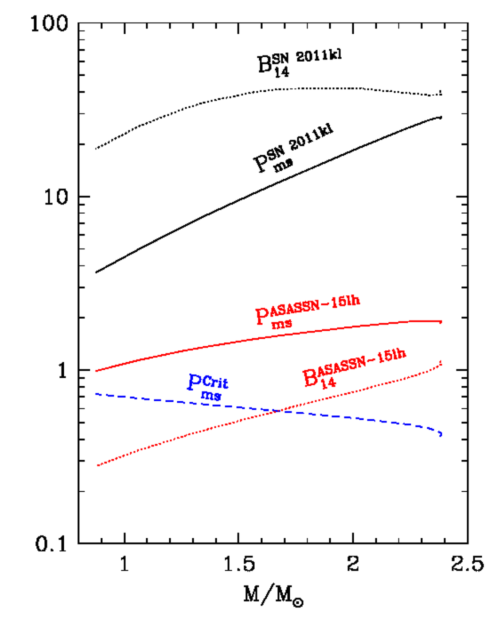
Our hydrodynamical calculations simulate the explosion of an evolved star, followed consistently until core collapse condition (calculated by Nomoto & Hashimoto, 1988). The spin-down timescale, t_p, and magnetar energy loss rate, L_p, are the free parameters to be determined by fitting the observed LC. They are afterwards translated to the magnetic field B and initial period P as a function of the magnetar mass.

ASASSN-15lh

ASASSN-15lh has been claimed as the most luminous SN ever discovered. It belongs to Type Ic (lacking hydrogen) class. Chatzopoulos et al. (2016) examine some of the few viable interpretations.

We have explored our parameter space by computing a set of magnetar models to analyze the LC of ASASSN-15lh . In the Figure below, left pannel shows our results for a pre-SN He star of 4 $M_\odot$ with M_{cut}= 1.5 $M_\odot$ and M_{ej} = 2.5 $M_\odot$ (thin red line) and for a more massive model of He star 8 $M_\odot$ with M_{cut}= 2 $M_\odot$ and M_{ej} = 6 $M_\odot$ (thick blue line). We assumed an initial explosion energy of 5.5×10^{51} erg although this has a minor effect on the results. The magnetar parameters are in this case $L_p = 9\times10^{45}$ erg s^{-1} and $t_p = 40$ days. For the less massive model the overall LC shape is not well reproduced.

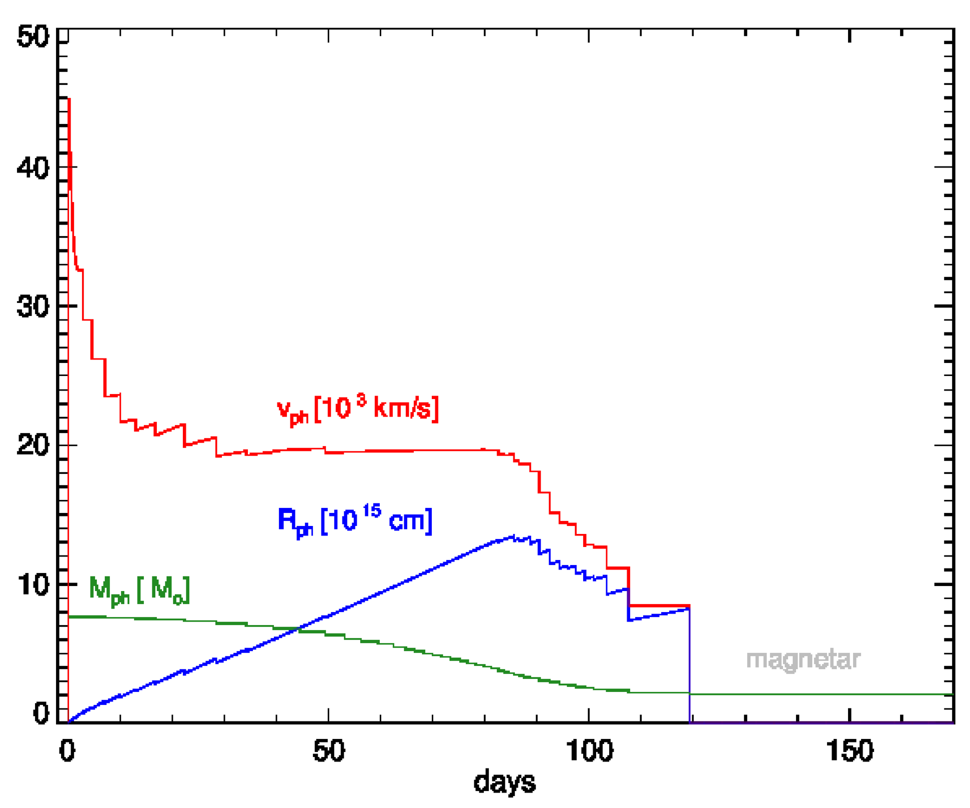




$$L_p = \frac{4\pi^4 R^6}{3c^3}\frac{B^2}{P^4}$$
$$t_p = \frac{3c^3 I_{NS}}{\pi^2 R^6}\frac{P^2}{B^2}$$
$$L = L_p\left(1+\frac{t}{t_p}\right)^{-2}$$

Observed bolometric LC of ASASSN-15lh (Dong et al. 2016) compared with models of 4 $M_\odot$ (dashed line) and 8 $M_\odot$ (solid line) pre-SN mass for magnetar parameters of $L_p = 9\times10^{45}$ and $t_p = 40$ days and t_{exp} = JD 2457143. Note that the uncertainty regarding t_{exp} could modify the exact value of the parameters.

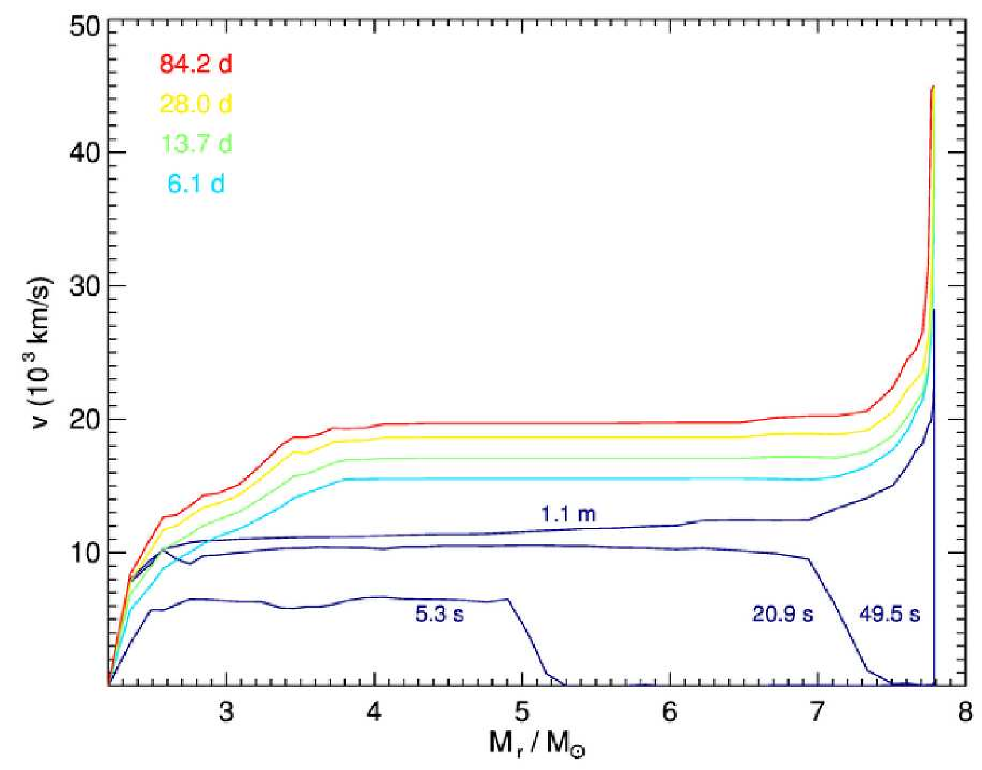
At ~ 100 days, the photosphere reaches the inner regions where the magnetar energy is directly deposited. The observable effect of this fact deserve further investigation, because it could potentially be related to the UV rebrightening of ASASSN-15lh observed using Swift. This speculation is also motivated by the lack of evidence of interactions between the ejecta and circumstellar medium throughout all the observed spectra (see Godoy-Rivera et al. 2016).



Evolution of the photospheric properties: velocity, radius and mass enclosed, for the OPAL tables with an opacity floor of 0.2 cm^2 g^{-1} corresponding to the electron scattering opacity for hydrogen free material.
The fit is sensible to κ, usually assumed as a gray opacity in LC magnetar models in the literature. In any case, the scope of this analysis is to show that the magnetar scenario is plausible for this object and not to provide definitive values of the physical parameters.

Dynamic effect

Our treatment of the SN evolution illustrates the importance of the dynamical effects on the ejecta, especially in cases of powerful magnetars. The homologous expansion, usually assumed in SN studies, can be broken because of the additional energy source. The extra heating source due to the magnetar swell the inner zones and produces larger velocities and a flat profile that raise steeply only at the outermost layers.



Velocity profile for our preferred model of 8 $M_\odot$. In this extreme case the external radial zones inflates up to $0{,}15\,c$.

Conclusions

We were able to reproduce the bolometric LC of ASASSN-15lh in the context of magnetar-powered models with physically allowed parameters (the NS rotating below breakup point). We found a total energy release by the magnetar of $E \sim 3\times10^{52}$ erg, which is one order of magnitude larger than the initial explosion energy. This is also close to the brightest event plausible to be magnetar driven (Metzger et al. 2015).

The mechanism that channels a fraction of the energy released in the collapse to the ejected mass is not explicit in our model. It is possible that the magnetar, having all the neccesary ingredients, do form jets. In our 1D study such details cannot be taken into acount, but this unknown energy can be considered to be part of the kinetic energy E_k of the mass ejected in the explosion. In addition to the explosion energy, we have considered the magnetar and a reasonable amount of ^{56}Ni .

At this state the scenario is still far from self consistent, but it stands between the most promising ones to explain ASASSN-15lh.

References

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