ON THE INDUCED GRAVITATIONAL COLLAPSE SCENARIO

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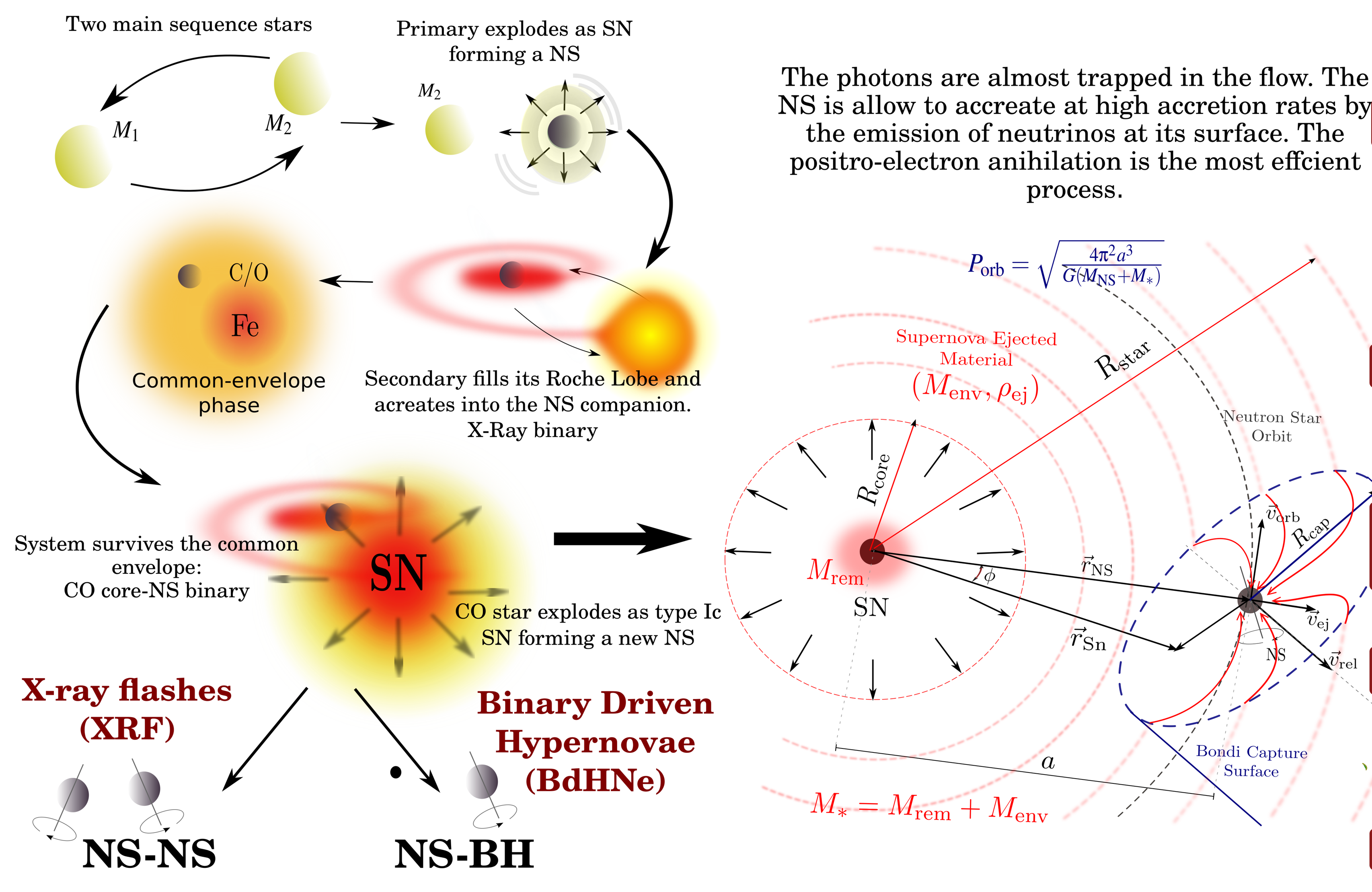
ABSTRACT

The induced gravitational collapse (IGC) paradigm has been successfully applied to the explanation of GRB-SNe and X-ray flashes (XRF). The progenitor is a tight binary system composed of a CO core and a neutron star (NS) companion. The explosion of the SN leads to hypercritical accretion onto the NS companion. In a first scenario, also referred as binary-driven hypernova (BdHNe), the CO-NS binary is enough bound ($a < 10^{11}$ cm), so the accretion rate onto NS grows up to $> 10^{-2}\, M_\odot/s$, this allows to the NS reach its critical mass, and collapses to a black hole (BH) with a GRB emission with $E_{iso} > 10^{52}$ erg. A second scenario can happen for binary systems with larger binary separations, then the hypercritical accretion onto the NS is not sufficient to induced its gravitational collapse. Instead of a GRB emission, a X-ray flash (XRF) is produced with $E_{iso} < 10^{52}$ erg. We present numerical simulations of the IGC. We simulate the SN explosion and the hydrodynamic evolution of the accreting material falling into the Bondi-Hoyle surface of the NS. We address the observational features of this process and its detectability occurring during the different phases of the IGC process: from the early accretion, to the possible collapse of the companion NS to a BH, to the interaction of the radiation of the above accretion process with the supernova ejecta.

Induced Gravitational collapse scenario



Long Bursts

Progenitor	CO_{core}-NS	
SN	Always	
	$E_{iso} < 10^{52}$ ergs	$E_{iso} > 10^{52}$ ergs
Sub-class	XRF	BdHN
BH	NO	YES
Hard spectrum	NO $E_{p,i}$<200 KeV	YES $E_{p,i}$>200 KeV
X-ray	YES (no scaling)	YES (scaling)
Gev	NO	YES
Outcome	NS-NS	BH-NS

Figure 1: The theoretical framework and the first estimates of the hypercritical accretion onto the NS as a function of the nature of the binary parameters were first presented in Rueda and Ruffini, ApJ, 758 (2012) and continuing studied Fryer, et al. ApJ, 793 (2014), Becerra, et al., ApJ, 812 (2015), Fryer, et al., Phys. Rev. Lett., 115 (2015), Becerra, et al., ApJ, 833 (2016) and Ruffini, et. al, ApJ, 832 (2016)

HYPERCRITICAL ACCRETION INDUCED BY THE SUPERNOVA AND NS GRAVITATIONAL COLLAPSE

The rate at which the neutron star accretes mass can be estimate through the Bondi-Hoyle formalism (Hoyle and Lyttleton, 1939; Bondi and Hoyle, 1944; Bondi, 1952):

$$\dot{M}_B(t) = \pi \rho_{ej} R_{cap}^2 \sqrt{v_{orb}^2 + v_{ej}^2 + c_{s,ej}^2} \qquad \text{with} \qquad R_{cap} = \frac{2GM_{NS}}{v_{orb}^2 + v_{ej}^2 + c_{s,ej}^2}, \tag{1}$$

where G is the gravitational constant, ρ_{ej} is the density of the SN ejecta, $c_{s,ej}$ the sound speed of the ejected material and v_{ej} the ejecta velocity. Assuming a homologous expansion for the ejected material, the **SN-velocity** and the **SN-density** evolve as:

$$v_{ej}(r,t) = n\frac{r}{t} \Rightarrow \begin{cases} R_{star}(t) = R_{0_{star}}\left(\frac{t}{t_0}\right)^n \\ v_{star}(t) = v_{0_{SN}}\left(\frac{t}{t_0}\right)^{n-1} \end{cases} \quad \text{and} \quad \rho_{ej}(x,t) = \rho_{ej}^0\left(\frac{r}{R_{star}(t)}, t_0\right)\frac{M_{env}(t)}{M_{env}(t_0)}\left(\frac{R_{0_{star}}}{R_{star}(t)}\right)^3$$

with ρ_{ej}^0 the pre-supernova density profile and R_{star} the outermost layer of the SN ejecta.

Table 1: Properties of the pre-supernova CO cores obtained with the Kepler Stellar Evolution code (Woosely et. al, 2002).

Analitical fit: $\rho_{ej}^0 = \hat{\rho}_{core} \ln\left(\frac{r}{\hat{R}_{core}}\right)\left(\frac{R_{star}}{r} - 1\right)^m$

Progenitor M_{ZAMS} ($M_\odot$)	ρ_{core} (10^8 g cm^{-3})	R_{core} (10^7 cm)	M_{env} ($M_\odot$)	R^0_{star} (10^9 cm)	m
15	3.31	5.01	2.079	4.49	2.771
20	3.02	7.59	3.89	4.86	2.946
30	3.08	8.32	7.94	7.65	2.801

If we want to discriminate the binary parameters of the systems in which the NS can reach, by accretion, its critical mass (M_{crit}) and consequently collapse to a BH, from the systems in which the accretion is not enough to induce such a collapse, we need to determine how the NS evolves during the accretion process. In general, the evolution of the NS gravitational mass, M_{NS} can be written:

$$\dot{M}_{NS}(t) = \frac{\partial M_{NS}}{\partial M_b}\dot{M}_b + \frac{\partial M_{NS}}{\partial J_{NS}}\dot{J}_{NS}, \tag{2}$$

where J_{NS} and M_b are the NS angular momentum and baryonic mass.

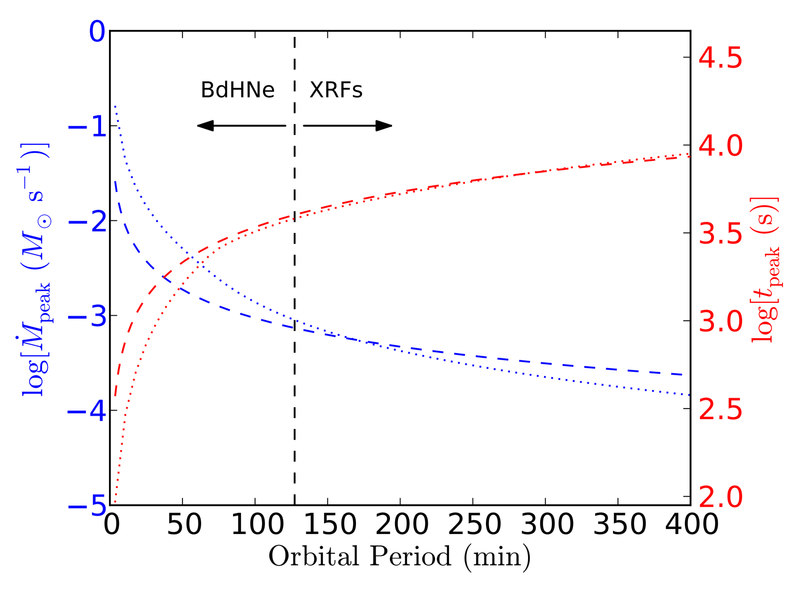
We assume that all the mass entering the NS capture region will be accreted by the NS as baryonic mass (Cipolletta et al, 2015):

$$M_b(t) = M_b(t_0) + M_B(t), \qquad \text{with} \qquad \frac{M_b}{M_\odot} = \frac{M_{NS}}{M_\odot} + \frac{13}{200}\left(\frac{M_{NS}}{M_\odot}\right)^2\left(1 + \frac{1}{137}j_{NS}^{1.7}\right), \tag{3}$$

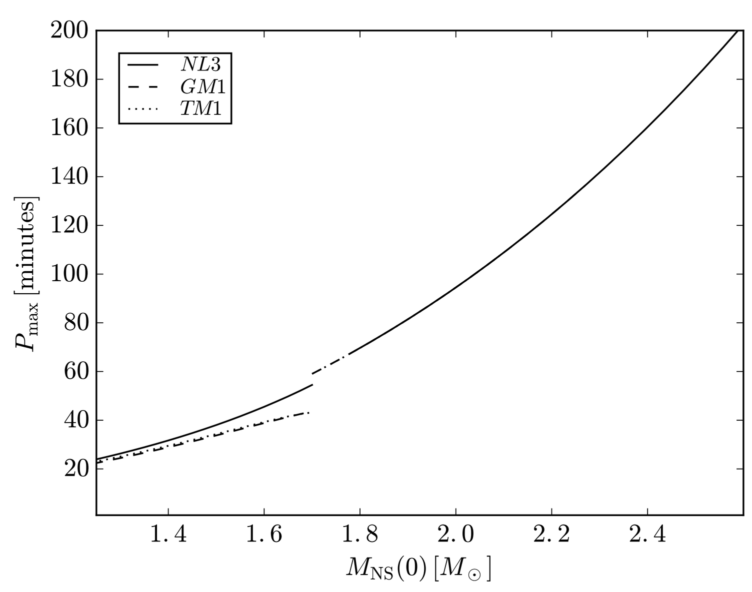
Then, by angular momentum conservation, the torque on the NS by accretion is:

$$\dot{J}_{NS} = \xi l(R_{in})\dot{M}_B \qquad \text{with} \qquad \xi < 1 \qquad \text{and} \qquad l(R_{in}) = \begin{cases} l_K(R_{NS}), & \text{for } R_{NS} > r_{lso} \Rightarrow R_{in} = R_{NS}, \\ l_{lso}, & \text{for } R_{NS} \le r_{lso} \Rightarrow R_{in} = r_{lso}. \end{cases} \tag{4}$$

where R_{in} is the disk inner boundary radius, $l(R_{in})$ is the angular momentum per unit mass of the material located at $r = R_{in}$, and ξ is the efficiency of the angular momentum transfer.



(a) Peak accretion rate ($\dot{M}_{peak}$) and peak time (t_{peak}) as a function of the orbital period. This example corresponds to a CO core from the $20\ M_{ZAMS}$ progenitor, a $2.0\ M_\odot$ NS mass



(b) Maximum orbital period for which the NS with initial mass $M_{NS}(0)$ collapses to a BH by accretion of supernova ejecta material.

SUPERNOVA EJECTA ASYMMETRIES INDUCED BY THE NS

For supernova explosions occurring in close binaries with compact companions such as NSs or BHs, like the case of the IGC scenario, the supernova ejecta is subjected to a strong gravitational field which produces a deformation of the supernova fronts closer to the accreting companion. In order to visualize this, we have simulated the evolution of the supernova layers in the binary system by dividing the SN ejecta in N particles of different mass and following its three-dimensional motion under the action of the gravitational field of the orbiting NS. We have varied the NS gravitational mass with equations (1) and (2) and also, we have removed from the simulation the particles that are crossing the Bondi-Hoyle radius.

Snapshots of the supernova ejecta density on the binary equatorial plane in the IGC scenario. The initial binary system is formed by a $2\ M_\odot$ NS and the CO-core of a $30\ M_{zams}$ progenitor.

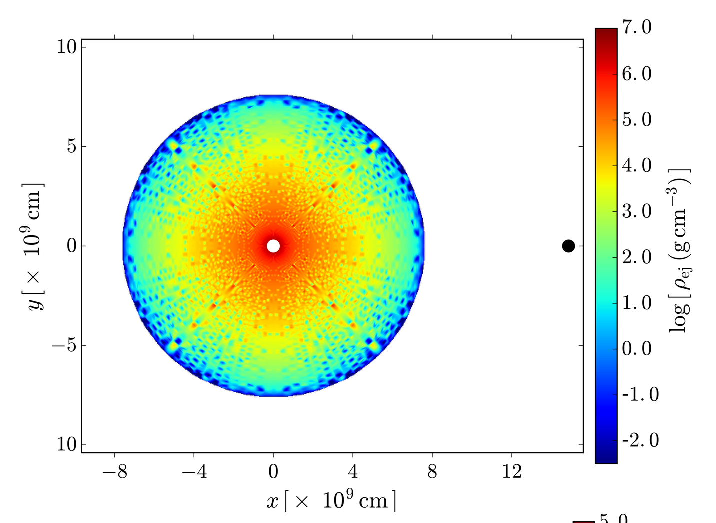
$$N = N_r \times N_\theta \times N_\phi$$
$$\Delta\theta = (\pi/2)/N_\theta\ ;\ \Delta\phi = 2\pi/N_\phi$$
$$x = \log(r)$$
$$\Delta x = (x_s - x_c)/N_r$$
$$x_s = \log(R_{star})\ ;\ x_c = \log(R_{core})$$

Thickness of each layer:

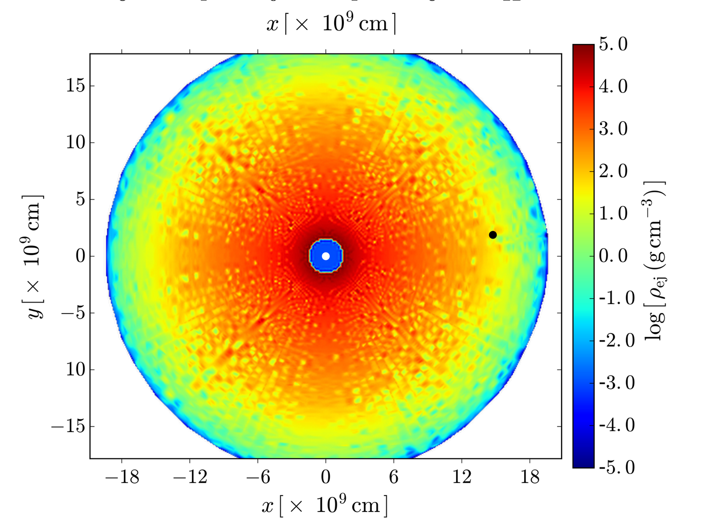
$$\Delta r = r_i(10^{\Delta x} - 1).$$

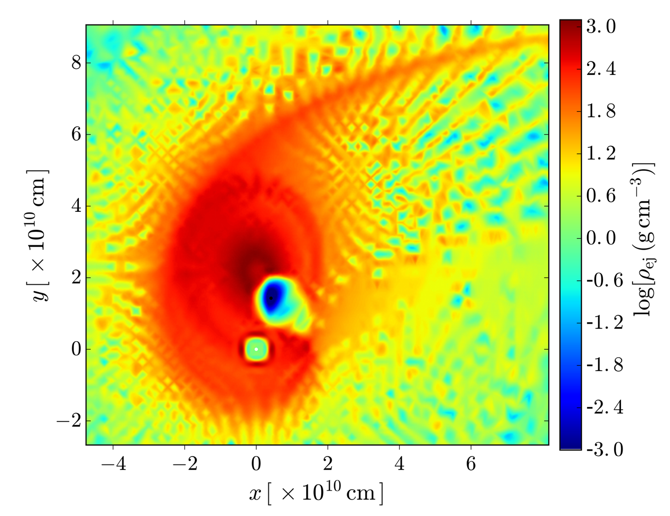
Mass of each particle in the i-layer is:

$$m_i = 4\pi r_i^3 \ln(10)\Delta x \rho(r_i)/(2N_\theta N_\phi).$$

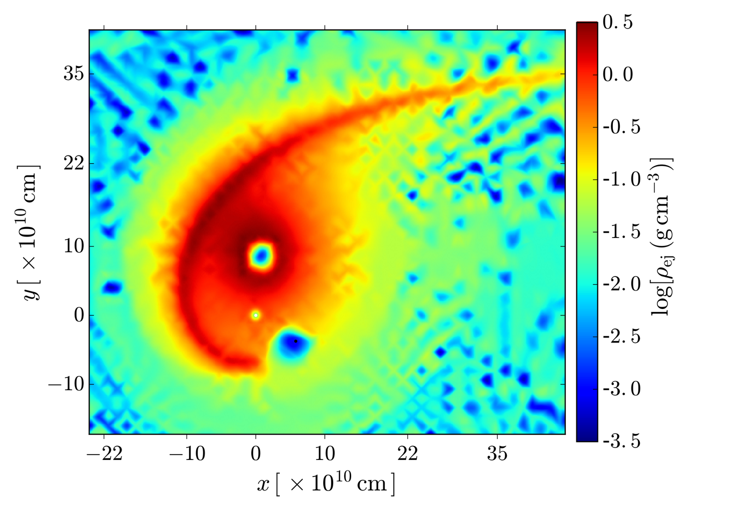


Owing to their fast velocity, the accretion rate of the first layers is low and they escape almost undisturbed, so the supernova ejecta at these times keeps its original spherical symmetry.





P_{orb} = 5 min at 100 s after the collapse of the NS.



P_{orb} = 50 min at $t \approx$ 44 min.. In this case the NS does not collapse.

It sees the increasing asymmetry of the supernova ejecta around the orbital plane.

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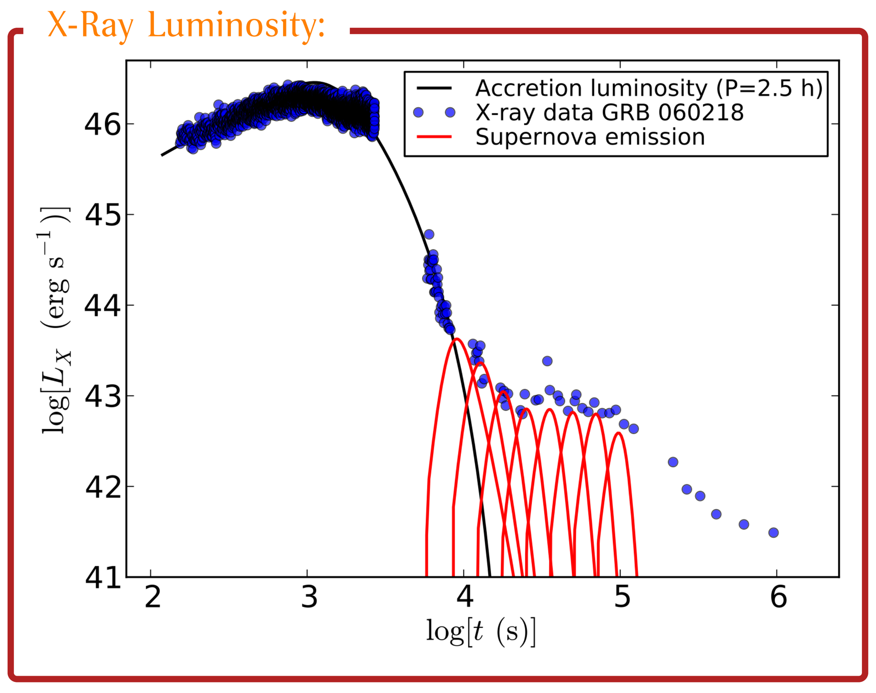
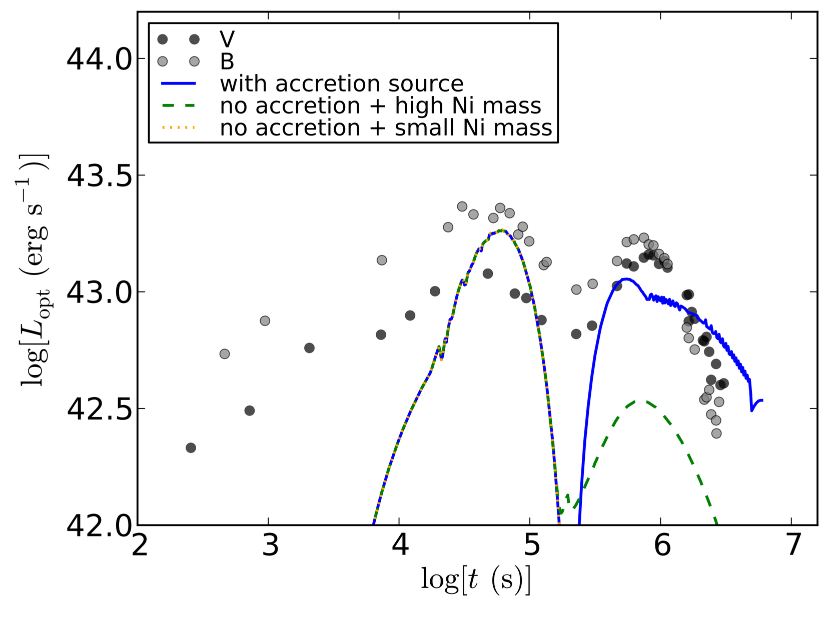
X-Ray Luminosity:



The early part of the light-curve ($t \lesssim 10^3$ s) has been fitted with the luminosity expected from the accretion process onto the NS companion ($L_{acc} = (\dot{M}_b - \dot{M}_{NS})c^2$). For the long-lasting X-ray plateau in the afterglow (at times $t \sim 10^3$–10^6 s) we need to analyze the emission of the supernova at early stages. We have calculated the shock breakout luminosity using the light-curve code described in Bayless et al. (2015). To simulate the energy that the hypercritical accretion process onto the NS adds to the ejecta, we injected it as an energy source at the base of the explosion and to mimic the asymmetries in the SN ejecta, caused by the NS companion presence, we have modeled a series of spherical explosions with different densities. We assume an initial explosion energy of 2×10^{51} erg, ranging the spherical equivalent-mass from 0.05–4 $M_\odot$.

Optical and UV luminosity (Pian et al. 2006):



The light-curve in both bands peaks first near 50,000 s and then again at 500,000 s. Using our 1 $M_\odot$ 1D model from our X-ray emission, we simulate the V and B band light-curves. Without either ^{56}Ni decay or accretion energy, the supernova explosion only explains the first peak. However, if we include the energy deposition from the accretion onto the NS (for our energy deposition, we use 4×10^{46} erg s^{-1} over a 2500 s duration), our simulations produce a second peak at roughly 500,000 s. A second peak can also be produced by increasing the total ^{56}Ni yield. However, even if we assume half of the total ejecta is ^{56}Ni, the second peak remains too dim to explain the observations.