A white dwarf in a binary as the progenitor of superluminous SN 2006gy

A. Simaz Bunzel[1,2] M. C. Bersten[2,3,4] G. Folatelli[2,3,4]

[1] Instituto Argentino de Radioastronomía (CCT La Plata, CONICET; CICPBA; UNLP), C.C.5, (1894) Villa Elisa, Buenos Aires, Argentina

[2] Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, B1900FWA La Plata, Argentina

[3] Instituto de Astrofísica de La Plata (IALP), CONICET, Argentina

[4] Kavli Institute for the Physics and Mathematics of the Universe, Todai Institutes for Advanced Study, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan

ABSTRACT

The progenitor nature of superluminous supernovae, events in which the radiated energy is 100 times higher than in normal supernovae, is a highly-debated topic. SN 2006gy is one of the first observed superluminous supernovae, in which the spectrum showed narrow hydrogen lines implying interaction with a circumstellar medium. Although the nature of this event remains unclear, it was recently proposed that a standard type Ia supernova hitting with a shell of circumstellar medium can produce a light curve matching the observations. In this work, we explore this scenario by evolving a grid of isolated binaries of different initial masses and orbital periods, using the publicly-available stellar-evolution code *MESA*. We follow the evolution of both stars from their initial stages in the main-sequence until the formation of a white-dwarf orbiting around a massive donor star. We map the initial binary parameter space able to produce these systems, estimate rates of SN 2006gy-like events and study the dependence of our predicted rates with respect to the mass of the circumstellar medium.

Context

Despite being one of the most luminous and first observed superluminous supernova (SLSN) with detailed photometric and spectroscopic observations, the nature of SN 2006gy is still being discussed. Recently, it has been proposed that it was due to the explosion of a white-dwarf (WD) inside a dense, hydrogen-rich circumstellar material (CSM) [1].

Motivation

- Such scenario can successfully explain the presence of Fe I lines in the nebular spectrum as arising from the ejecta of the Type Ia SN (SN Ia). Additionally, the CSM would be responsible for the observed hydrogen lines.

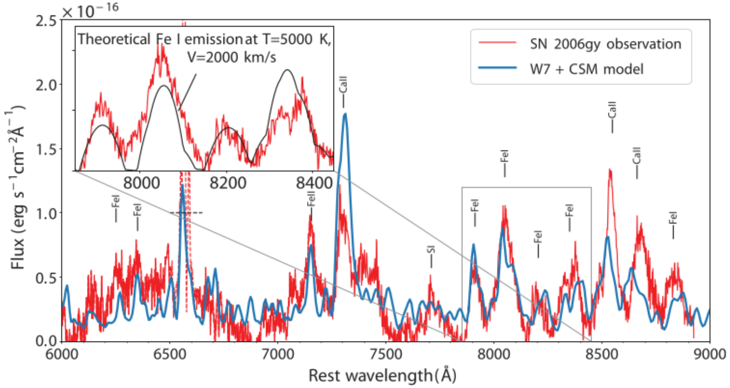

Figure 1: Observed spectrum of SN 2006gy at +394 days after explosion (Figure adapted from [1]).

- The luminous light curve is therefore explained by the interaction between the SN Ia ejecta and the CSM. In this binary configuration, a common-envelope (CE) phase can help synchronize the envelope ejection (and formation of the CSM) with the supernova explosion. The alternative case of a core-collapse explosion inside the CSM is disfavored because it would produce a too luminous event.

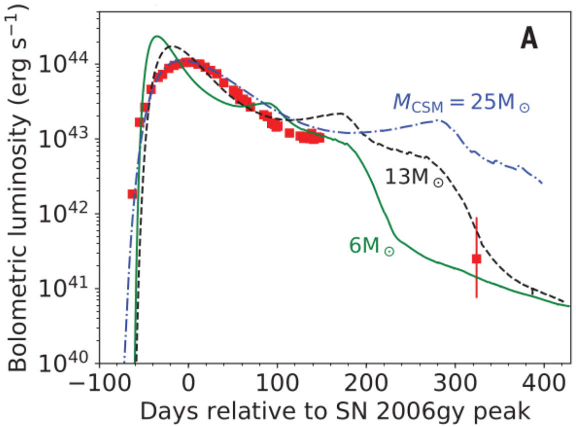

Figure 2: Comparison between different models of light curves for a type Ia + CSM and SN 2006gy observations (Figure adapted from [1]).

Methods

We compute a grid of non-rotating binary systems with different initial masses and orbital periods using *MESA*. We start when both stars with masses $M_{1,i}$ and $M_{2,i}$ are at the zero-age main sequence (ZAMS), in circular orbits, with an initial period $P_{orb,i}$ and having a solar-metallicity content of $Z = 0.017$ (consistent with measurements of the metallicity in the host galaxy of SN 2006gy). All of the mass-transfer (MT) phases are assumed to be completely conservative, implying that the only mass that is lost from the system is due to the stellar winds of the stars. We terminate our simulations when the initially less massive star (i.e., the star having a mass $M_{2,i}$) overflows its Roche lobe (RLO), which happens after the initially more massive one has become a WD.

In order to estimate expected properties for the desired configuration, we weight our simulations by assuming distribution functions for initial binary parameters (mass function, mass ratios and orbital periods) [2], [3]. Additionally, we consider the chemical evolution of the Universe [4] impacting the star formation rate (SFR) [5] and a standard ΛCDM cosmology to connect redshift with cosmic time.

Schematic evolution

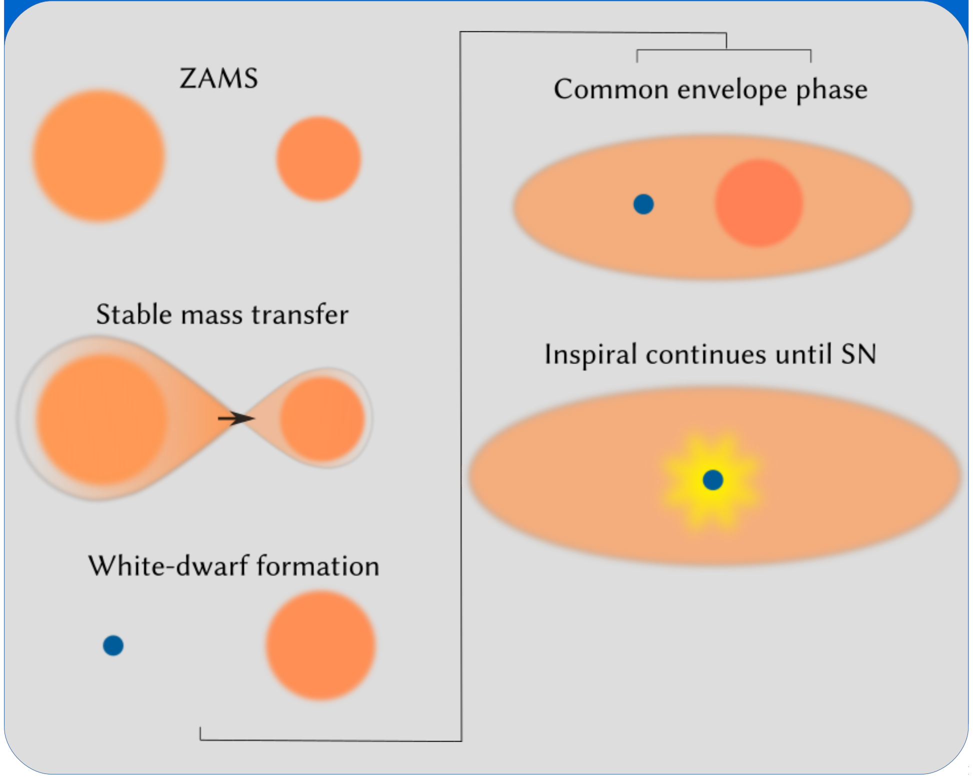

Figure 3: Illustration of the binary stellar evolution leading to a type Ia SN explosion inside a dense environment.

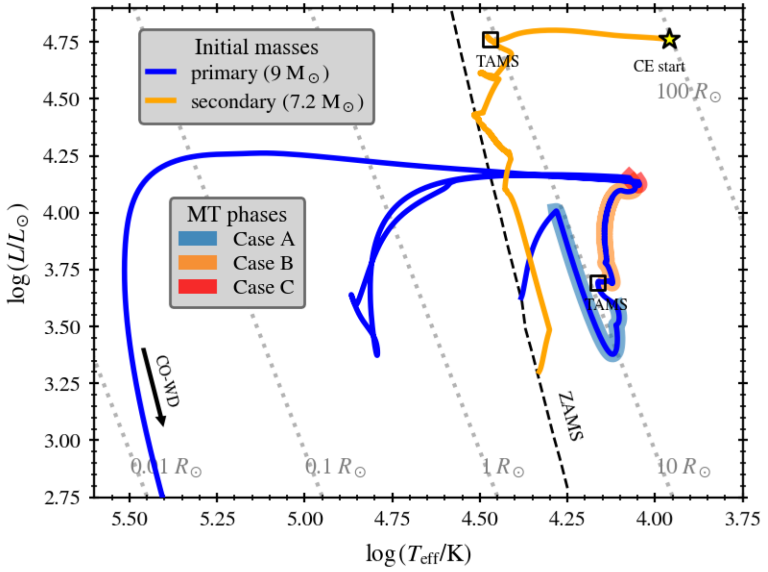

Figure 4: Evolutionary tracks on the HR diagram of both components of a binary system with a primary star of 9 solar masses and a secondary of 7.2 solar masses in a circular orbit of period 3.16 days. Solid blue line follows the evolution of the primary star; while solid orange line tracks the evolution of the companion star. The black dashed line corresponds to the ZAMS positions of solar composition stars. Case A (B and C) of MT is indicated in light-blue (orange and red) above the primary evolutionary track. Square symbols marks the end of the MS for each of the stars and a yellow star represents the place when the secondary overflows its Roche lobe while having a white-dwarf as a companion.

Results: Example of a binary evolution

The primary and initially most massive star evolves faster than its companion and overflows its Roche lobe during its main-sequence (MS) evolution (Case A of MT). The secondary upon accretion, evolves to higher luminosities keeping almost a constant effective temperature. Once the primary swells enough after leaving the MS, it starts a new MT phase in which the remaining hydrogen-rich envelope of the primary is removed. After detachment, the primary evolves in a blue-to-red-ward loop until a third and short MT follows (Case C). After that, the primary cools down as a CO WD.

During the WD cooling phase, the secondary evolves off the MS until it overflows its corresponding Roche lobe (yellow star in Figure 4). Given the high mass-ratio at the onset of this last MT phase, it will likely proceed in an unstable way such that a CE is expected to develop inside of which the WD could be completely disrupted in a SN Ia [6].

Grid of binary systems

The region of compatible progenitors is constrained to have an initially primary star with a mass below 11 solar masses and orbital periods < 100 days, independently of the initial mass-ratio. Both Case A and B of MT can produce a progenitor system for SN2006gy.

We find that the increase in the initial mass-ratio widens the region with the desired configuration.

Additionally, for primaries below 4 solar masses there will not be enough mass in the CSM to be a progenitor of SN 2006gy [1], while above 11 solar masses the core mass of the primaries after He burning will be larger than the Chandrasekhar mass.

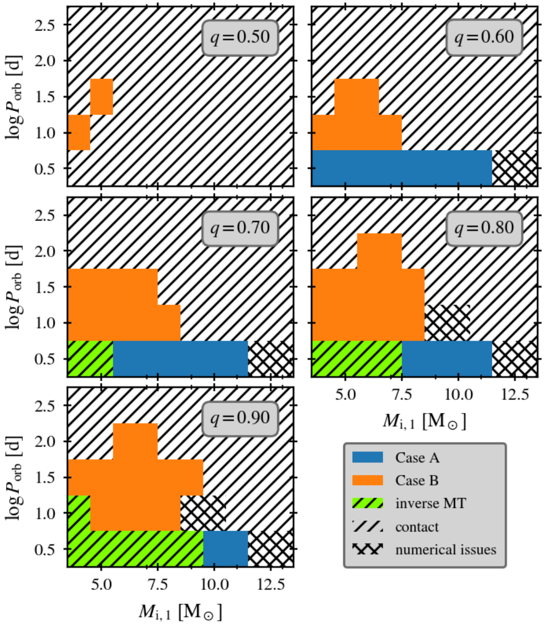

Figure 5: Initial parameter space and their outcome for all mass-ratios explore in this work. Squares with no hatches are models which are stopped when the secondary overflows its Roche lobe while having a WD companion; light-blue (orange) colors represent the first case of MT that happened during their evolution as shown in the label. White squares represent binaries where both stars are overflowing their lobes. Single and double hatching models will not produce the desired configuration of a star transferring mass to a WD companion.

Rates

There is a clear trend of decreasing rates with the increasing mass of the envelope of the donor star. Although with a low value, it is plausible for this channel to explain the derived CSM mass from light-curve modeling [1]. However, above 13 solar masses we find no solutions: this evolutionary channel fails at explaining such large masses.

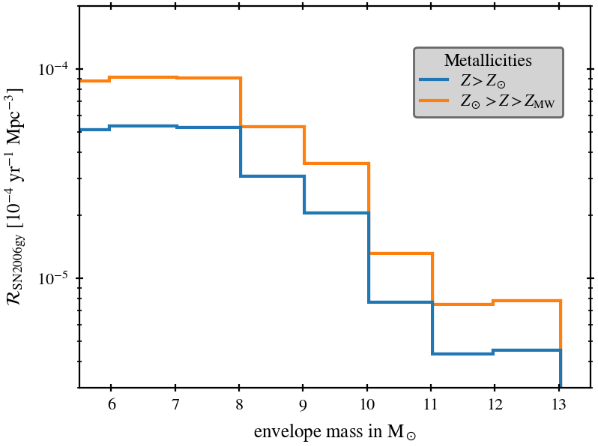

Figure 6: Co-moving volumetric rates at redshift zero for binaries in which a star is transferring mass (in an unstable case) to a WD as a function of envelope masses. The SFR is assumed to be 0.01 solar masses per year, value taken from evaluating the SFR at the redshift estimated for the formation of the progenitor population of SN 2006gy.

CONCLUSIONS

- This evolutionary channel is able to produce a WD orbiting around a massive overflowing donor star, which given the high mass-ratio between them will likely go through a CE phase. As a consequence of the short orbital separation at the onset of this CE phase, the release orbital energy might not be enough to unbind the envelope of the star, such that a merger is expected.

- Comparison of our derived rates to the observed ones [7] are almost an order of magnitude lower. Thus this channel cannot be the dominant to explain all the observed type II SLSNe, but rather a sub-population of them which share similarities to SN 2006gy (such as SN 2006tf, SN 2008fz and SN 2008am).

- Given the computational difficulties in the modeling of a CE phase, it is still not clear how the merger could lead to a SN Ia. We plan to study the reaction of the envelope of the donor star to the inspiral of the WD and how the accretion onto the WD proceeds.

References

[1] Jerkstrand, A., Maeda, K., & Kawabata, K. S.2020, Science, 367, 415
[2] Salpeter, E. E. 1955, ApJ, 121, 161
[3] Sana, H., de Mink, S. E., de Koter, A., et al. 2012,Science, 337, 444
[4] Langer, N., & Norman, C. A. 2006, ApJL, 638,L63
[5] Madau, P., & Fragos, T. 2017, ApJ, 840, 39
[6] Chevalier, R. A. 2012, ApJL, 752, L2
[7] Quimby, R. M., Yuan, F., Akerlof, C., & Wheeler,J. C. 2013, MNRAS, 431, 912