

The morphology of the X-ray afterglows and of the jetted GeV emission in long gamma-ray bursts

Press release

What is the fate of very massive binary stars, which kind of signatures/observables are associated with their stepwise evolution, which kind of new physical laws are revealed, represent the most relevant questions at the heart of relativistic astrophysics. The answer to these questions is intimately related to the explanation of the most powerful transients in the Universe, supernovae (SNe) and gamma-ray bursts (GRBs), and with the formation of neutron star-black hole (NS-BH), of neutron star-neutron star (NS-NS), and possibly BH-BH binaries. A crucial question then arises: how large are the mass and how fast are the rotational spin of those astrophysical BHs and NSs?

A clue to this answer comes out from decades of electromagnetic observations of X-ray binaries in which a BH accretes mass from a stellar companion. From their continuous monitoring, it has turned out that these BHs have masses ranging $\sim 5\text{--}20 M_{\odot}$, where the upper edge is given by the very recently updated mass of the BH harbored by the X-ray binary Cygnus X-1 [1]. While the origin of X-ray binaries is well established, focus is needed to identify the evolutionary channels leading to the onset of GRBs, to their time evolution, as well as to the new physical laws and astrophysical regimes envisaged for their description.

In a new article published in the Monthly Notices of the Royal Astronomical Society [2], an ICRA-ICRANet research team (some of them INAF associates) sheds light on the mass and spin of stellar-mass BHs from an extensive analysis of long-duration GRBs. This has been allowed by fifty years of exponential growth of multiwavelength observations of GRBs and theoretical progress, from which it has been possible to identify the “inner engine” of the GRB, and verify the validity of the BH mass-energy formula established fifty years ago. The subject of study are 380 energetic long GRBs with energy release above 10^{52} erg in gamma-rays, all with a measured cosmological redshift, and an X-ray afterglow. These systems are accompanied by an SN of type Ic, namely an SN produced by a star which has lost its hydrogen and helium layers. The binary-driven hypernova (BdHN) scenario of long GRBs bridges what we know from binary evolution, with high-energy relativistic astrophysics to explain these extreme systems.

The GRB progenitor system is a binary composed of a carbon-oxygen (CO) star and a companion NS. During their long lifetime, a very massive binary experiences several stages, each one characterized by specific physical phenomena and observables (see left side of Figure 1). The more massive of the two stellar components evolves faster through the nuclear burning phases, leading it to make a first SN explosion, with consequent formation of a NS. Mass-transfer from the ordinary stellar component to the NS leads to an X-ray binary stage. Further binary interactions lead to multiple common envelope phases in which mass loss is enhanced and the ordinary star gets rid of its outer low-density envelope, forming a CO star. The binary orbit shrinks while thermonuclear evolution of the CO star proceeds until its iron core becomes unstable against gravitational collapse, forming a new NS (ν NS) at its center, and driving an SN explosion. At this point, a powerful transient starts and its ultimate fate depends crucially on the distance separating the exploding CO star and the NS companion. The SN ejected material triggers a massive accretion process onto the NS companion as well as onto the ν NS by matter fallback (see Figure 2).

For compact binaries with orbital periods of the order of 5 minutes (see right side of Figure 1), the companion NS accretes sufficient matter to trigger its gravitational collapse, forming a BH which emanates a distinct, associated emission at high-energies (GeV) characterized by a luminosity as a function of time that follows a power-law. The fallback accretion onto the ν NS and its pulsar emission power the GRB X-ray and optical afterglow, characterized by power-law luminosities, different from the one of the GeV emission. BdHNe forming a BH have been called of type I.

From the statistics of the GeV emission, it has been inferred the morphology of the GRB emission process: it occurs within a conical region of 60° measured from the normal to the orbital plane. No GeV radiation is observable outside such a conical region. The X-ray afterglow is instead present in all the BdHN I, independently of the inclination angle of the GRB with respect to the orbital plane. This detailed understanding have allowed the team to infer, from the analysis of the X-ray afterglow, the spin and magnetic field of the ν NS. The analysis of the GeV emission have led, for the first time in about fifty years of GRB observations, to directly evaluate the precise mass and spin of the BHs formed in these powerful transients. The specific mass and spin of 11 BHs have been obtained and they range $2.3\text{--}8.9 M_{\odot}$ and $0.27\text{--}0.87$, respectively.

This treatment of long GRBs, originating from the very massive binary stars, makes ample use of a description based on the four fundamental interactions: relativistic gravity and electrodynamics describe the “inner engine”, weak

interactions drive the neutrino emission in the accretion process, and the strong interactions shape the inner structure of the NSs responsible of the X-ray afterglow.

Since the pioneering observations of BATSE instrument on board the Compton satellite [3], we know that GRBs are isotropically distributed when mapped in galactic coordinates. Similarly, following the discovery of their cosmological redshift thanks to BeppoSAX [4], observations of BdHN I have occurred all the way to $z = 8.2$ (e.g. GRB 090423 [5, 6]). We can safely assert that GRBs, also thanks to their outstanding energetics, have a fundamental role in relativistic astrophysics processes in the 95.5% of our known Universe. Their prolonged emission of polarized synchrotron radiation in the X-rays and in the GeV regime may well have a fundamental role in the life in and of our Universe.

Having said all the above, it comes as a surprise the vision carried forward by the LIGO-Virgo observatories that very massive binary stars should rapidly gravitationally collapse, evolve into two BHs, crossing the spacetime of our Universe, finally merging into a larger BH. Such a vision avoids the role of any fundamental interactions with the sole exception of gravity, which seems at odds with the field of relativistic astrophysics.

Contact:

Prof. Remo Ruffini

Director, ICRANet

Phone: (+39) 085 2305 4201, mobile: (+39) 339 475 2566

E-mail: ruffini@icra.it

-
- [1] J. C. A. Miller-Jones, A. Bahramian, J. A. Orosz, I. Mandel, L. Gou, T. J. Maccarone, C. J. Neijssel, X. Zhao, J. Ziłkowski, M. J. Reid, et al., *Science* **371**, 1046 (2021), 2102.09091.
 - [2] R. Ruffini, R. Moradi, J. A. Rueda, L. Li, N. Sahakyan, Y. C. Chen, Y. Wang, Y. Aimuratov, L. Becerra, C. L. Bianco, et al., *MNRAS* (2021), 2103.09142.
 - [3] W. S. Paciesas, C. A. Meegan, G. N. Pendleton, M. S. Briggs, C. Kouveliotou, T. M. Koshut, J. P. Lestrade, M. L. McCollough, J. J. Brainerd, J. Hakkila, et al., *Astroph. J. Supp.* **122**, 465 (1999), astro-ph/9903205.
 - [4] M. R. Metzger, S. G. Djorgovski, S. R. Kulkarni, C. C. Steidel, K. L. Adelberger, D. A. Frail, E. Costa, and F. Frontera, *Nature (London)* **387**, 878 (1997).
 - [5] R. Salvaterra, M. Della Valle, S. Campana, G. Chincarini, S. Covino, P. D’Avanzo, A. Fernández-Soto, C. Guidorzi, F. Mannucci, R. Margutti, et al., *Nature (London)* **461**, 1258 (2009), 0906.1578.
 - [6] R. Ruffini, L. Izzo, M. Muccino, G. B. Pisani, J. A. Rueda, Y. Wang, C. Barbarino, C. L. Bianco, M. Enderli, and M. Kovacevic, *Astron. Astroph.* **569**, A39 (2014), 1404.1840.
 - [7] J. A. Rueda, R. Ruffini, M. Karlica, R. Moradi, and Y. Wang, *Astroph. J.* **893**, 148 (2020), 1905.11339.
 - [8] L. Becerra, C. L. Ellinger, C. L. Fryer, J. A. Rueda, and R. Ruffini, *Astroph. J.* **871**, 14 (2019), 1803.04356.

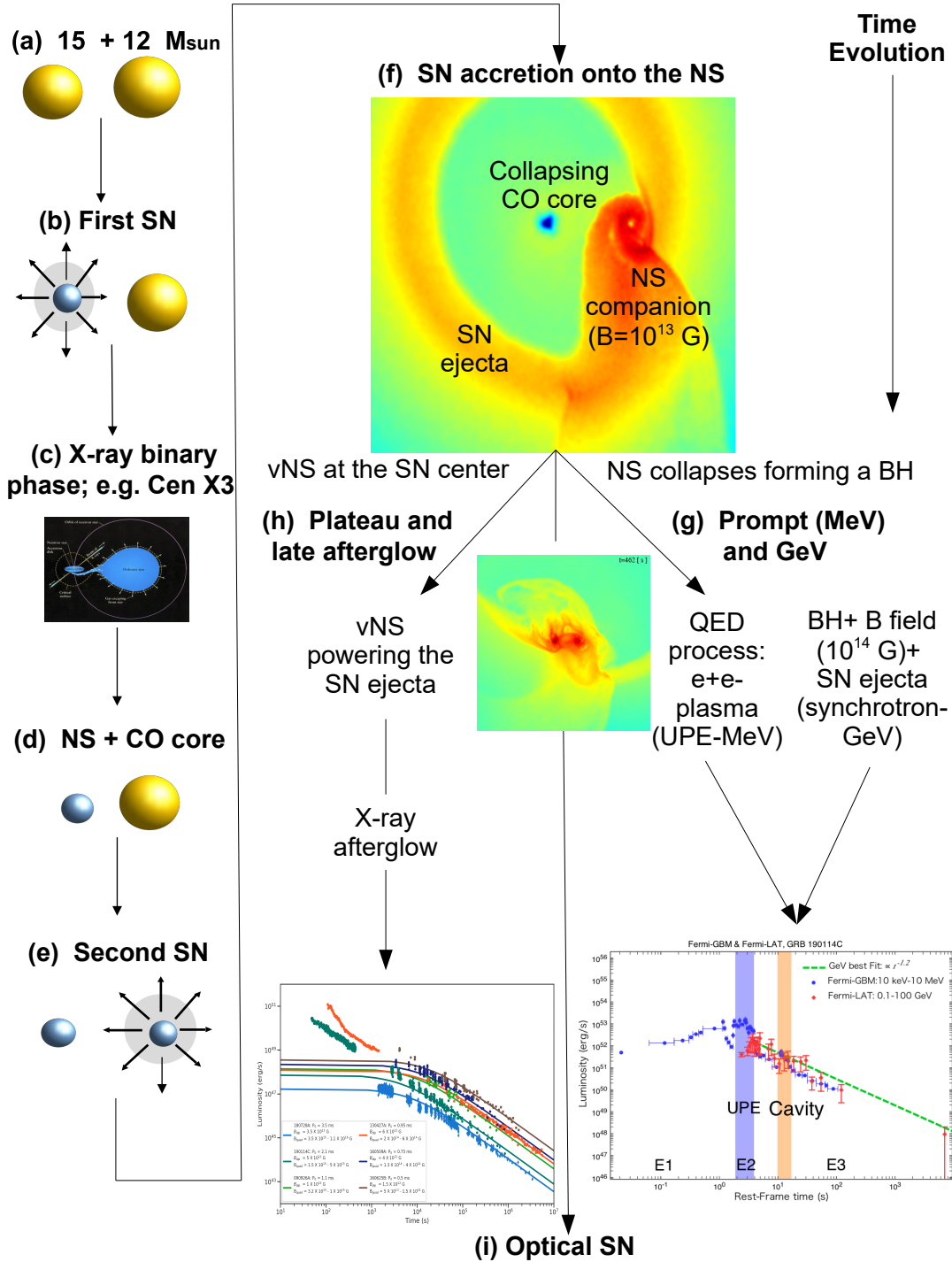


FIG. 1. Taken from [7]. Schematic evolutionary path of a massive binary up to the emission of a BdHN. (a) Binary system composed of two main-sequence stars, say 15 and 12 M_{\odot} , respectively. (b) At a given time, the more massive star undergoes the core-collapse SN and forms a NS (which might have a magnetic field $B \sim 10^{13}$ G). (c) The system enters the X-ray binary phase. (d) The core of the remaining evolved star, rich in carbon and oxygen, for short CO star, is left exposed since the hydrogen and helium envelope have been stripped by binary interactions and possibly multiple common-envelope phases (not shown in this diagram). The system is, at this stage, a CO-NS binary, which is taken as the initial configuration of the BdHN model [8]. (e) The CO star explodes as SN when the binary period is of the order of few minutes, the SN ejecta of a few solar masses start to expand and a fast rotating, newborn NS, for short ν NS, is left in the center. (f) The SN ejecta accrete onto the NS companion, forming a massive NS (BdHN II) or a BH (BdHN I; this example), depending on the initial NS mass and the binary separation. Conservation of magnetic flux and possibly additional MHD processes amplify the magnetic field from the NS value to $B \sim 10^{14}$ G around the newborn BH. At this stage the system is a ν NS-BH binary surrounded by ionized matter of the expanding ejecta. (g) The accretion, the formation and the activities of the BH contribute to the GRB prompt gamma-ray emission and GeV emission. (h) X-ray afterglow powered by the fallback accretion and pulsar-like emission of the ν NS. (i) Optical emission of the SN due to nickel decay in the ejecta.

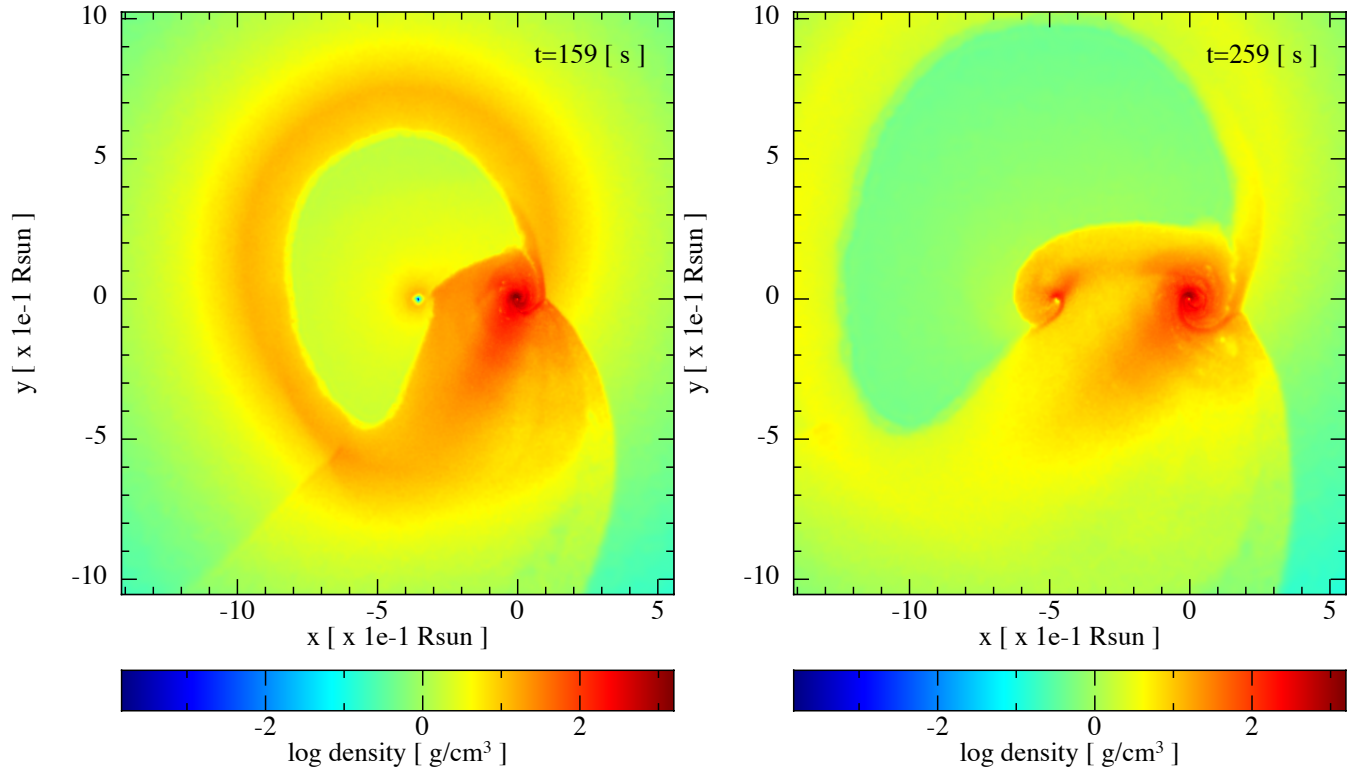


FIG. 2. A SPH simulation from Becerra et al. [8] of the exploding CO-star as the SN in the presence of a companion NS. The CO-star is obtained from the evolution of a $25 M_{\odot}$ zero-age main-sequence (ZAMS) progenitor which leads to a pre-SN CO-star mass $M_{\text{CO}} = 6.85 M_{\odot}$. The initial mass of the ν NS (formed at the center of the SN) is $1.85 M_{\odot}$ and the one of the NS companion is $M_{\text{NS}} = 2 M_{\odot}$. The initial orbital period is 4.8 min. The panels show the mass density on the binary equatorial plane at two selected times from the SN explosion ($t = 0$ of the simulation), 159 s and 259 s. The reference system is rotated and translated so that the x-axis is along the line that joins the ν NS and the NS, and the axis origin (0,0) is located at the NS position. In this simulation, the NS collapses when it reaches $2.26 M_{\odot}$ and angular momentum $1.24 GM_{\odot}^2/c$, while the ν NS is stable with mass and angular momentum, respectively, $2.04 M_{\odot}$ and $1.24 GM_{\odot}^2/c$. Up to the final simulation time, the binary system kept bound although the binary orbit widens, reaching an orbital period of 16.5 min and an eccentricity of $\epsilon = 0.6$. The collapse of the NS to the newly-formed BH, characteristic of a BdHN I, occurs at $t = 21.6$ min.