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Magnetic field and rotation of the newborn neutron star in binary-driven hypernovae inferred from the X-ray afterglow of long gamma-ray bursts

Press release

The change of paradigm in gamma-ray burst (GRBs) physics and astrophysics introduced by the binary driven hypernova (BdHN) model, proposed and applied by the ICRA-ICRANet-INAF members in collaboration with the University of Ferrara and the University of Côte d'Azur, has gained further observational support from the X-ray emission in long GRBs. These novel results are presented in the new article [1], published on April 20, 2020, in The Astrophysical Journal, co-authored by J. A. Rueda, Remo Ruffini, Mile Karlica, Rahim Moradi, and Yu Wang.

The GRB emission is composed by episodes: from the hard X-ray trigger and the gamma-ray prompt emission, to the high-energy emission in GeV, recently observed also in TeV energies in GRB 190114C, to the X-ray afterglow. The traditional model of GRBs attempts to explain the entire GRB emissions from a single-component progenitor, i.e. from the emission of a relativistic jet originating from a rotating black hole (BH). Differently, the BdHN scenario proposes GRBs originate from a cataclysmic event in the last evolutionary stage of a binary system composed of a carbon-oxygen (CO) star and a neutron star (NS) companion in close orbit. The gravitational collapse of the iron core of the CO star produces a supernova (SN) explosion ejecting the outermost layers of the star, and at the same time, a newborn NS (νNS) at its center. The SN ejecta trigger a hypercritical accretion process onto the NS companion and onto the νNS. Depending on the size of the orbit, the NS may reach, in the case of short orbital periods of the order of minutes, the critical mass for gravitational collapse, hence forming a newborn BH. These systems where a BH is formed are called BdHN of type I. For longer periods, the NS gets more massive but it does not form a BH. These systems are BdHNe II. Three-dimensional simulations of all this process showing the feasibility of its occurrence, from the SN explosion to the formation of the BH, has been recently made possible by the collaboration between ICRANet and the group of Los Alamos National Laboratory (LANL) guided by Prof. C. L. Fryer (see Figure 1 and [2]).

The role of the BH for the formation of the high-energy GeV emission has been recently presented in The Astrophysical Journal in [3]. There, the "inner engine" composed of a Kerr BH, with a magnetic field aligned with the BH rotation axis immersed in a low-density ionised plasma, gives origin, by synchrotron radiation, to the beamed emission in the MeV, GeV, and TeV, currently observed only in some BdHN I, by the Fermi-LAT and MAGIC instruments. In the new publication [1], the ICRA-ICRANet team addresses the interaction of the νNS with the SN due to hypercritical accretion and pulsar-like emission. They show that the fingerprint of the νNS appears in the X-ray afterglow of long GRBs observed by the XRT detector on board the Niels Gehrels Swift observatory. Therefore, the νNS and the BH have well distinct and different roles in the long GRB observed emission.

The emission from the magnetized νNS and the hypercritical accretion of the SN ejecta into it, gives origin to the afterglow observed in *all* BdHN I and II subclasses. The early ($\sim$few hours) X-ray emission during the afterglow phase is explained by the injection of ultra-relativistic electrons from the νNS into the expanding ejecta, producing synchrotron radiation (see Figure 2). The magnetic field inferred from the synchrotron analysis agrees with the expected toroidal/longitudinal magnetic field component of the νNS. Furthermore, from the analysis of the XRT data of these GRBs at times $t \gtrsim 10^4$ s, it has been shown that the power-law decaying luminosity is powered by the νNS rotational energy loss by the torque acted upon it by its dipole+quadrupole magnetic. From this, it has been inferred that the νNS possesses a magnetic field of strength $\sim 10^{12}$–10^{13} G, and a rotation period of the order of a millisecond (see Figure 3). It is shown in [1], that the inferred millisecond rotation period of the νNS agrees with the conservation of angular momentum in the gravitational collapse of the iron core of the CO star which the νNS came from.

The inferred structure of the magnetic field of the "inner engine" agrees with a scenario in which, along the rotational axis of the BH, it is rooted in the magnetosphere left by the NS that collapsed into a BH. On the equatorial plane, the field is magnified by magnetic flux conservation.

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[1] J. A. Rueda, R. Ruffini, M. Karlica, R. Moradi, and Y. Wang, Astroph. J. **893**, 148 (2020), 1905.11339.

[2] L. Becerra, C. L. Ellinger, C. L. Fryer, J. A. Rueda, and R. Ruffini, Astroph. J. **871**, 14 (2019), 1803.04356.

[3] R. Ruffini, R. Moradi, J. A. Rueda, L. Becerra, C. L. Bianco, C. Cherubini, S. Filippi, Y. C. Chen, M. Karlica, N. Sahakyan, et al., Astroph. J. **886**, 82 (2019).

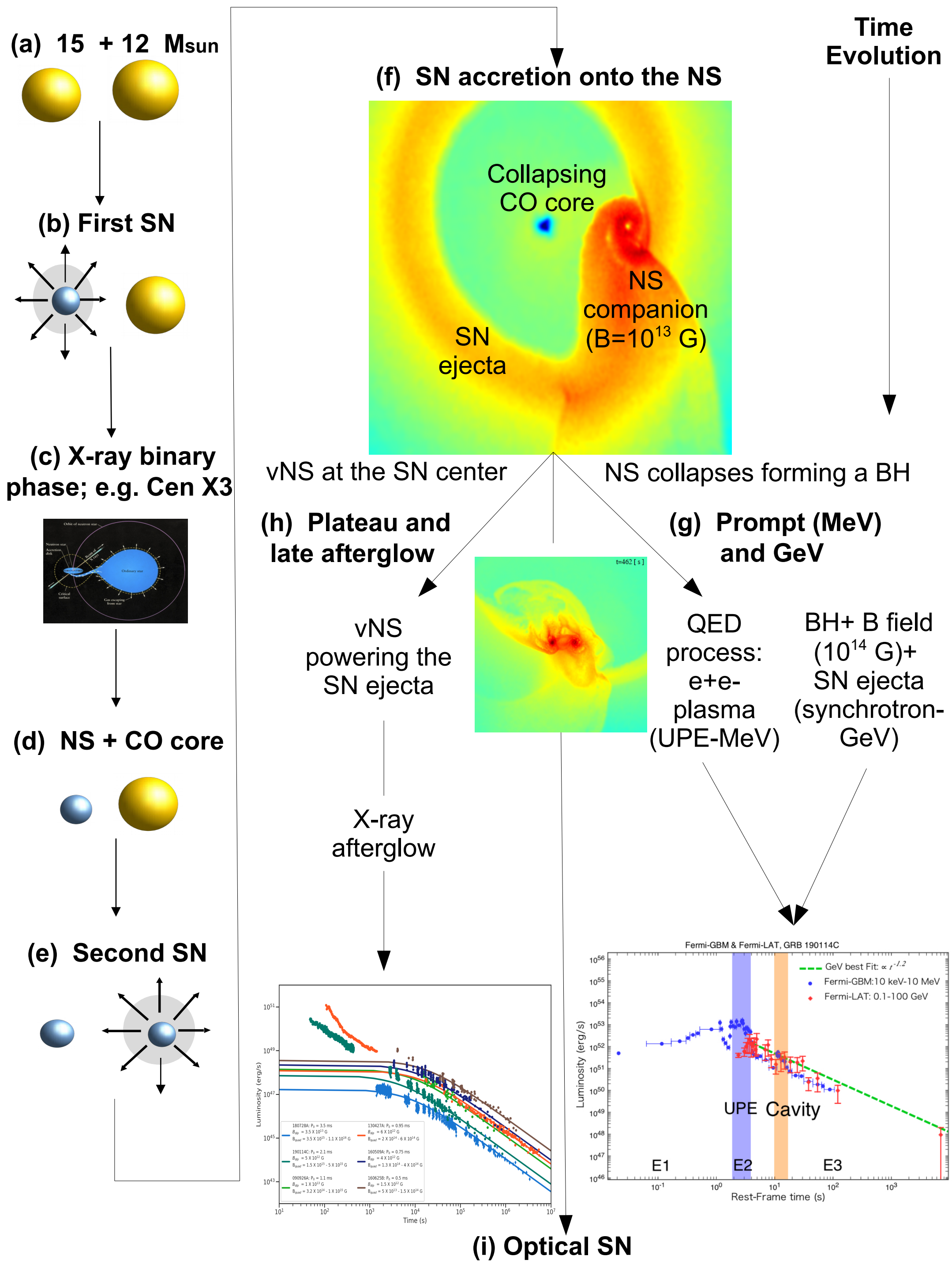

FIG. 1. Taken from [1]. Schematic evolutionary path of a massive binary up to the emission of a BdHN. (a) Binary system composed of two main-sequence stars, say 15 and 12 $M_\odot$, respectively. (b) At a given time, the more massive star undergoes the core-collapse SN and forms a NS (which might have 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 striped 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 [2]. (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 νNS, 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 νNS-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.

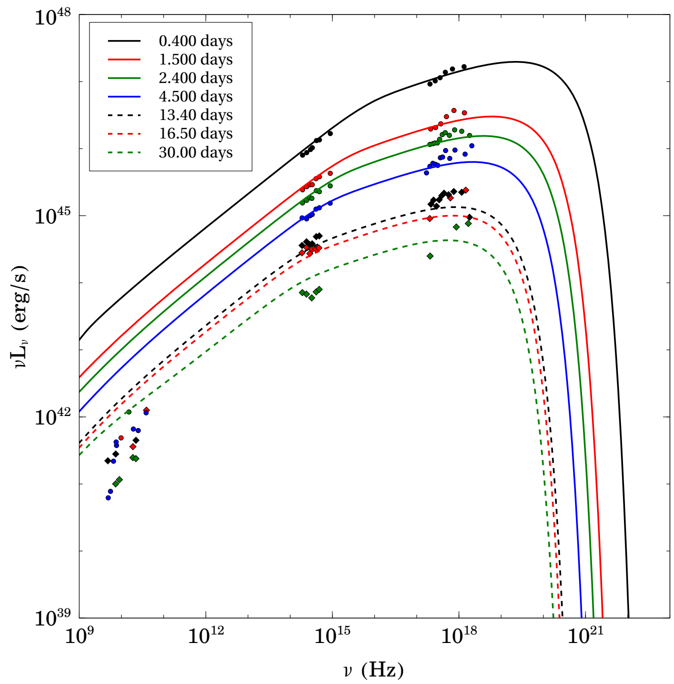

FIG. 2. Taken from [1]. Model evolution of synchrotron spectral luminosity at various times compared with measurements in various spectral bands for GRB 160625B.

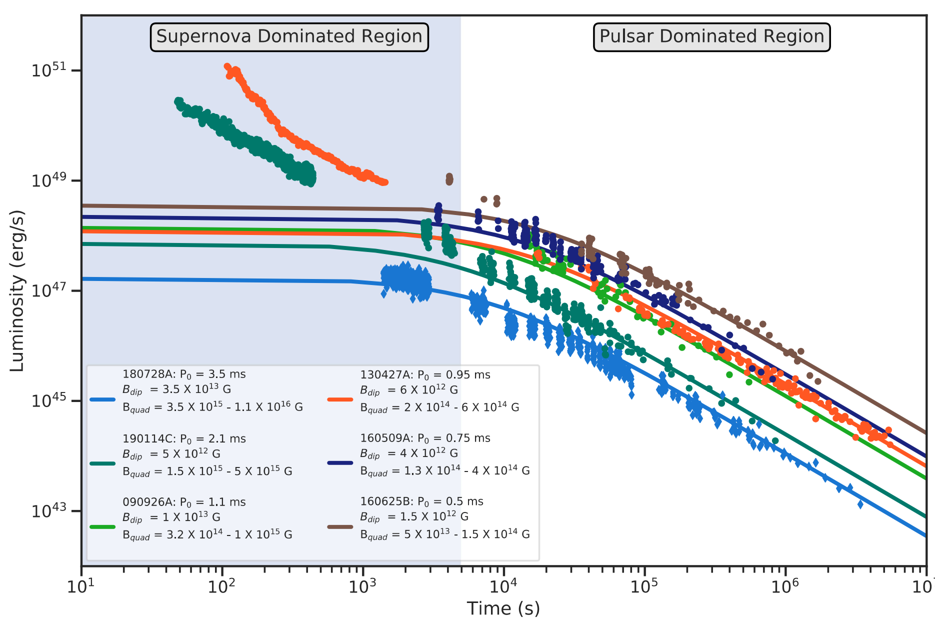

FIG. 3. Taken from [1]. The brown, deep blue, orange, green and bright blue points correspond to the bolometric (about ~ 5 times brighter than the soft X-ray observed by Swift-XRT data) light-curves of GRB 160625B, 160509A, 130427A, 190114C and 180728A, respectively. The solid lines are theoretical light-curves obtained from the rotational energy loss of the νNS powering the late afterglow ($t \gtrsim 5 \times 10^3$ s, white background), while in the earlier times ($3 \times 10^2 \lesssim t \lesssim 5 \times 10^3$ s, blue background), the kinetic energy of the SN ejecta plays also an important role. Because of the necessity of having a significant sample to extract the physical properties of the νNS (magnetic field and rotation rate), the analysis was limited to late part of the afterglow, say at times $t \gtrsim 3 \times 10^2$ s, where data are more available. At earlier times, only GRB 130427A and GRB 190114C in this same have available data.