GRB 190829A - A Showcase of Binary Late Evolution

GRB 190829A is the fourth closest gamma-ray burst (GRB) to date (z = 0.0785). Owing to its wide range of radio, optical, X-ray, and especially the very-high-energy (VHE) observations by H.E.S.S., it has become an essential new source examined by various models with complementary approaches.

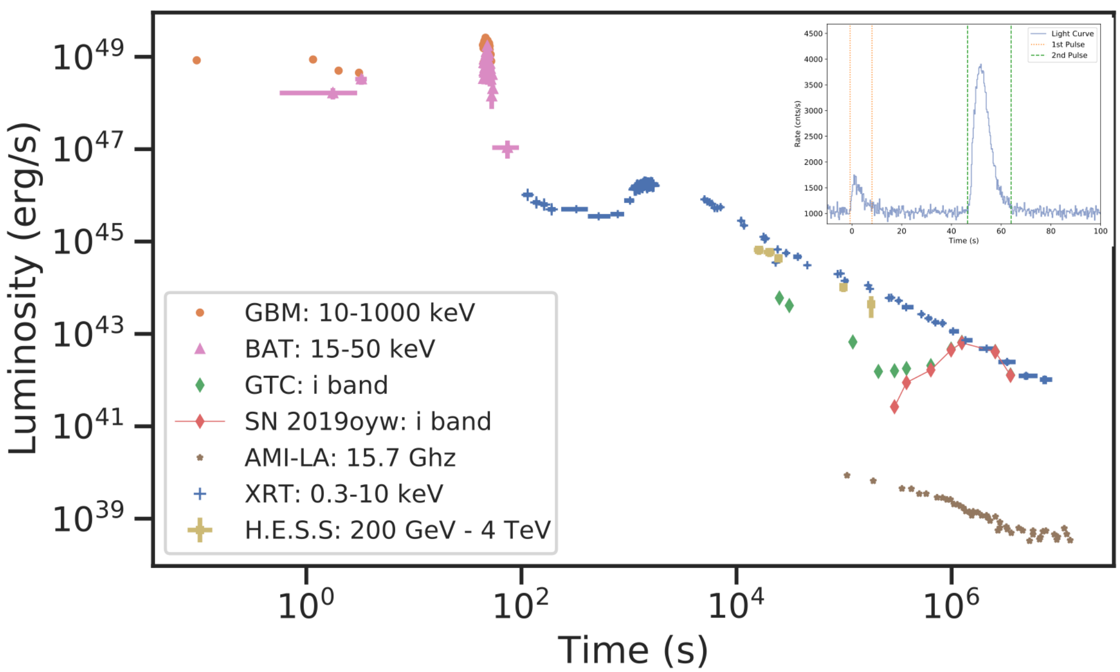

Fig 1: Luminosity of GRB 190829A including the data from H.E.S.S (yellow) for TeV, Fermi-GBM (orange dots), Swift- BAT (purple triangles) for the prompt emission of hard X-ray and gamma-ray, Swift-XRT (blue crosses) for the soft X-ray (absorbed), GTC (green diamonds) for the optical i band, from which the SN 2019yw is extracted (red diamonds), the optical signal of SN over-shots the optical emission from the synchrotron, and AMI-LA (brown stars) for the radio observation. Top-right corner: The count rate of GRB 190829A prompt emission from the raw data of Fermi-GBM: The first pulse is from −0.75 s to 8.05 s, indicated by the orange dotted line, and the second pulse is from 46.50 s to 64.00 s, indicated by the green dashed line.

The traditional fireball model of GRBs is based on a single system, at times indicated as a "collapsar", possibly a Black Hole (BH), giving origin to an ultra-relativistic jetted emission. The slowing down of such a jet in the interstellar medium has been assumed to explain the main properties of the GRBs in all wavelengths. These results have been expressed, prior to 2002, in many reviews, see e.g. Shemi and Piran 1990, Fishman and Meegan 1995, Piran 2000, Van Paradijs et al 2000, Meszaros 2002. The review of Meszaros traces back the historical developments of GRB theories at a time the observations were the domain of gamma-ray astronomy observed by the BATSE instrument in the 20 to 600 KeV and the EGRET instrument in the 20 MeV to 30 GeV both on board the Compton CGRO satellite.

Our model based on a binary system was proposed in 2012 (Rueda & Ruffini 2012) and has been in development for one decade. Our approach was motivated by an alternative set of data following the launching of the Beppo-SAX satellite with on board the Wide Field X-rays camera which promoted a direct collaboration between the gamma-ray community and the much larger X-ray community. In the meantime, indeed following the UHURU satellite, a large number of X-ray missions including the Einstein telescope, the Chandra telescope, and the XMM were developed leasing to the discovery of the first black hole in our galaxy , Cygnus X1, the binary X-ray sources, and the structure galactic halos. The extragalactic origin of the GRBs, made possible by the discovery of the X-ray afterglow, did open an additional collaboration with the new class of large optical telescopes including Keck and the VLT. A new era linking GRBs to supernovae started. New space missions followed by the AGILE telescope in the GeV range, the Neil Gehrels Swift Observatory and the Fermi telescope in the MeV, GeV and TeV, recently involving also the MAGIC telescopes. A detailed high-quality data from the new observations made clear the new complexity of the GRB structure, composed of selected independent episodes each one characterized by a specific spectral feature observed in their rest frame. We advanced in 2012 a basic change of paradigm based on binary systems: the Binary driven Hypernovae (BdHN). The physical picture evolved gradually including the needed physics that allowed to study of a wide range of binary parameters including the explosion energy, the mass, the binary separation, the density profile, the equations of state and et al., as well as the statistical analysis of different GRB components (Ruffini et al. 1999, 2000, 2010, 2015; Wang et al. 2015; Ruffini et al. 2018a,b; Wang et al. 2018; Ruffini et al. 2018c; Wang et al. 2019b; Ruffini et al. 2019; Rueda et al. 2020; Rueda & Ruffini 2020; Moradi et al. 2021b; Ruffini et al. 2021). The numerical simulations of the occurring physical processes have been upgraded from onedimension (Fryer et al. 2014) to two-dimensions (Becerra et al. 2015), to three-dimensions (Becerra et al. 2016, 2019). The latest simulations (Becerra et al. 2019) implemented a smoothed-particle-hydrodynamics (SPH) method, and examined a large selection of initial conditions and the outcomes of the binary system after the SN explosion, see Fig 1, Rueda et al. (2019) and Rueda et al. (2021) have reviewed the entire development process. The case of GRB 190829A is indeed the first detailed verification of the validity of a BDHN model in view of the exceptionality of the available data.

Unlike the traditional fireball model, the BdHN model considers a central engine that arises in the final evolutionary stage of the CO core in the presence of a binary NS companion. An SN explosion occurs, it triggers the GRB emission and generates a νNS. Therefore, in addition to the physical processes of single-star collapse models, we need to consider not only the binary interactions but also the appearance of the νNS, see Fig 1. The most influential interactions are the accretion of SN ejecta onto the NS companion and the fallback accretion onto the νNS spins it up. The afterglow is produced by the mildly relativistic expanding SN ejecta which contains a large number of electrons accelerated by the kinetic energy of the SN and the energy injection from the rapidly spinning νNS and its subsequently spin-down. Unlike the BdHN I, which were by the hypercritical accretion of the SN ejecta into the NS companion form a BH, here we describe GRB 190829A by a BdHN II where no BH is formed but a more massive NS.

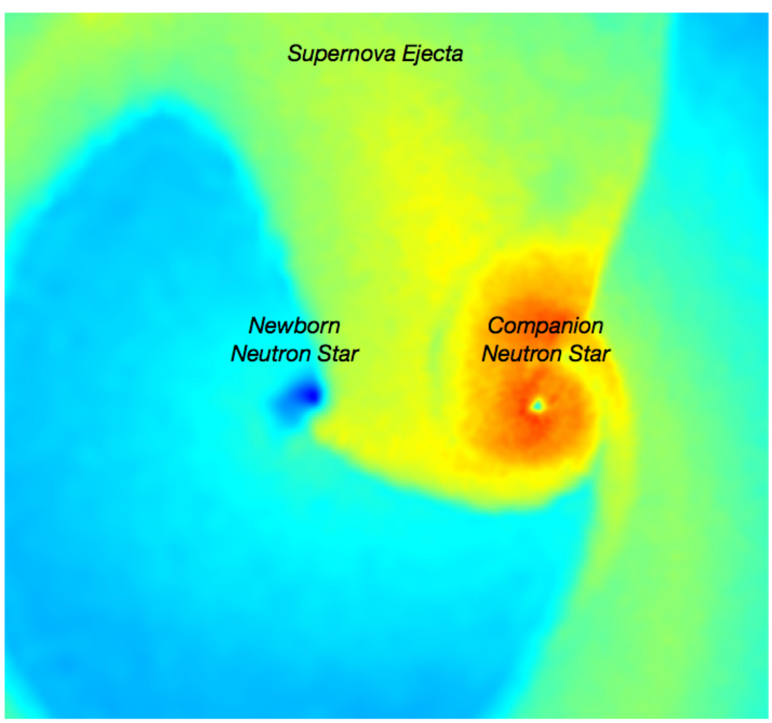

Fig 2. Ongoing accretion process onto the vNS and the NS companion simulated in Becerra et al. (2019). The vNS is located at the center of the dark blue spot, and is accreting the surrounding material. The SN ejecta are also being accreted by the NS companion, which is located at the center of the green spot. We also notice that the expansion of SN ejecta is distorted by the companion NS and a part of the SN ejecta is flowing back to the vNS. This process creates a unique feature of BdHNe: the fallback accretion onto the vNS is enhanced creating a second peak of accretion at about an orbital-period time after the SN explosion (see, e.g., Becerra et al. 2019, for more details).

The low redshift characteristic of GRB 190829A makes it possible to have detailed temporal observations of various bands, hence GRB 190829A becomes the first GRB to fully exhibit the final evolution of this special class of binary systems. Our BdHN II model has been successfully applied on this burst, explaining its prompt emission composed of two pulses, its radio, optical and X-ray afterglow, as well as the emergence of the SN signal, as follows:

As the COcore gravitationally collapses, an SN explosion occurs and a newborn NS (νNS) originates at its center. Most of the SN energy ($\sim 10^{53}$ erg) is deposited in the neutrino, about a few percent of energy goes to the kinetic energy of SN ejecta ($\sim 10^{51}-10^{52}$ erg), which expands outward at velocities of around 0.1 c. The low-density outermost layer has the highest speed while the denser regions expand with slower velocities. After a few minutes, the SN ejecta reaches the companion NS, and the hypercritical accretion starts. The accretion rate onto the companion NS rises exponentially and peaks in a few minutes. The numerical simulations show that the entire hypercritical accretion process may last for hundreds of minutes, but the peak accretion rate of more than 10^{-4} $M_\odot$ s^{-1}, supplied by the high density and slow-moving part of the SN ejecta, holds only for tens of seconds to tens of minutes depending on the binary separation, see Fig. 2, The accretion translates into an electromagnetic power of 10^{48}–10^{49} erg s^{-1} assuming a 10% of efficiency in the conversion from gravitational to radiation energy. This procedure of accretion onto the companion NS in a 20-40 minutes orbital period binary system well explains the first prompt pulse of GRB 190829A.

In the meanwhile, some matter falls back leading to an accretion process onto the νNS, see Fig 1. This fallback accretion is significantly amplified by the companion NS which alters the trajectory of a partial SN ejecta that flows back to the νNS. The accretion onto the νNS has two components, the first is the typical fallback matter the same as the case of the SN from a single star, it leads the accretion rate to reach a peak to then decay nearly as a power-law with time. The peak luminosity produced by it is weak < 10^{48} erg s^{-1} and can hardly be seen for cosmological distances. The second is the unique feature of the binary system, the presence of the companion enhances the fallback onto the νNS creating the second peak of accretion, see Fig 2. The second part contributes most to the accreting mass for a duration of about an orbital-period time. The fallback accretion also transfers angular momentum to the νNS, spinning it up to a rotation period of a few milliseconds. So the peak luminosity from the fallback accretion is in the order of 10^{48}–10^{49} erg s^{-1}. The fallback accretion onto the νNS explains the second prompt pulse of GRB 190829A.

The fallback accretion continues as a source injecting energy into the mildly relativistic expanding SN ejecta, as well as the spin-down energy from the νNS. The synchrotron emission from the SN ejecta leads to the afterglow. We adopt the associated synchrotron emission for explaining the radio, optical and X-ray afterglow emissions. Contrary to the traditional model which assumes the origin of synchrotron emission from an ultra-relativistic jet, we here assume that the ejecta expands at a constant velocity at a wide angle. Second, our magnetic field is from the νNS, we assume that at large distances from the νNS, beyond its light cylinder, the magnetic field decreases linearly with distance. This implies that the magnetic field strength felt by the expanding ejecta evolves with time. Third, the energy injection in the synchrotron originates from the fallback accretion and the spin-down of νNS. Our numerical computation shows that a νNS spinning at an 8 ms period with a dipole field of 5×10^{12} Gauss and quadrupole field of about $1x10^{14}$ Gauss, and an SN ejecta moving at 10^9 cm s^{-1} generates the observed radio, optical and X-ray afterglows.

We do not explain the origin of VHE emission observed in the 0.2–4 TeV energy band of H.E.S.S. neither by the above synchrotron model, nor the synchrotron self-Compton process: the synchrotron self-Compton emission peaks at a few hundreds of MeV, cutoffs at < 10 GeV, and has a lower luminosity to the observed in the H.E.S.S. energy bandwidth. However, the similar power-law behavior of the VHE and the X-ray light curves observed as well in GRB 190114C and GRB 180720B see e.g. Acciari et al., 2019 and Abdalla et al., 2019 allow us to advance the hypothesis the VHE can be related to some transient activity possibly related to a new physics originating in the νNS.

The BdHN model naturally contains an SN, which produces ~ $0.4M_\odot$ nickel whose radioactive decay energy is emitted mainly at optical wavelengths with a corresponding flux that peaks around ~ 13 days in the source rest-frame., common to all other GRBs (Aimuratov et al 2022, in preparation), and indeed it was observed by GTC.

Having succeeded in this special case of BdHN II GRB 190829A we are now progressing in the explanation of the BdHN I GRB 910114C and in the case of BdHN III GRB 170215A.