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On the formation of NS-NS and NS-BH binaries from binary-driven hypernovae

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The binary-driven hypernova (BdHN) model proposes an explanation for long gamma-ray bursts (GRBs) associated with type Ic supernovae (SNe). In this model, a binary system comprising a carbon-oxygen (CO) star and a neutron star (NS) companion undergoes various physical episodes, triggered by the core collapse of the CO star. This collapse leads to a SN explosion, forms a newborn NS (νNS) at its center and produces an accretion process on the νNS and the NS companion at super-Eddington rates. Using hydrodynamics simulations, we determine the maximum orbital period of the initial CO-NS binary that can stay bound after a BdHN event, resulting in NS-NS or NS-BH binaries. This provides insights into the outcomes of such cataclysmic events in binary systems.

We used the SN-SPH code (Fryer et al., 2006) to follow the evolution of the binary stars (the νNS and the NS companion) as the SN material expands. The simulations start when the SN shock front reaches the CO's outer radius. The νNS and NS, treated as point masses, interact gravitationally with SN ejecta particles and each other, while they can accrete additional particles from the SN ejecta (see Becerra et al. (2019) for more details of the simulations).

We perform simulations with a CO star coming from a progenitor with $M_{\rm zams} = 25M_\odot$ and a $2M_\odot$ and a $1.4M_\odot$ NS companion. At collapse , the CO star leaves a 1.85 $M_\odot$ νNS and ejects about 4.99 $M_\odot$ through the SN explosion. The code tracks the position and velocity evolution of all the SN ejecta particles as well as the point-mass particles. In order to determine whether the system remains gravitationally bounded, we compute the total energy of the νNS-NS system as:

$$E = \frac{1}{2}\frac{M_{\nu{\rm ns}}M_{\rm ns}}{M_{\nu{\rm ns}}+M_{\rm ns}}|\vec{v}_{\nu{\rm ns}}-\vec{v}_{\rm ns}|^2 - \frac{GM_{\nu{\rm ns}}M_{\rm ns}}{|\vec{r}_{\nu{\rm ns}}-\vec{r}_{\rm ns}|}, \quad (1)$$

where $(M_{\nu{\rm ns}}, \vec{r}_{\nu{\rm ns}}, \vec{v}_{\nu{\rm ns}})$ and $(M_{\rm ns}, \vec{r}_{\rm ns}, \vec{v}_{\rm ns})$ are the mass, vector position and velocity of the νNS and the NS companion, respectively. If the total binary energy becomes negative, $E < 0$, the remnant systems of a BdHNe event remain gravitationally bounded. Then, the CO-NS initial systems with the longest initial binary period, $P_{\rm orb,max}$, is the one that makes $E = 0.0$. Figure 1 shows the relation between $P_{\rm orb,max}$ and the SN energy, $E_{\rm sn}$. There is a maximum SN energy that will lead to bounded systems, otherwise, all binary systems will remain unbounded regardless of the initial binary period. The minimum SN energy is about 5.97×10^{50} ergs and 6.64×10^{50} ergs for the 1.4 $M_\odot$ and 2 $M_\odot$ NS companion, respectively.

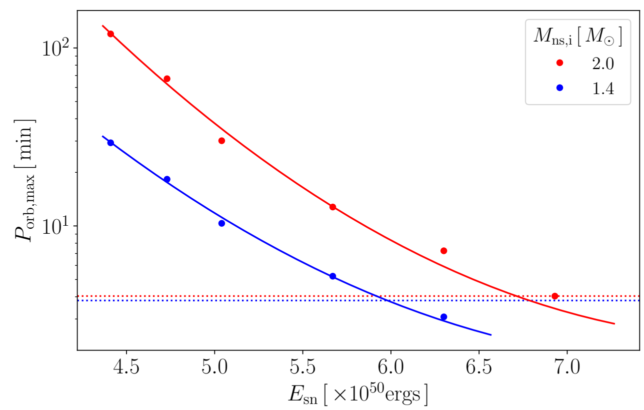

Figure 1. Longest initial binary period for which the outcome binary after a BdHne event remains bounded in function of the SN energy. The horizontal dotted lines represent the minimum period for the system, defined as the minimum binary separation at which there is no Roche-Lobe overflow before the SN explosion.

The final bounded systems will be compact binary systems (NS-NS or NS-BH), which will eventually merge through the emission of gravitational in 10^4 to 10^9 yrs. BdHNe I produces a series of rapidly merging NS-BH binaries that give rise to ultrashort gamma-ray flashes (U-GRFs) (Fryer et al., 2015).

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