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High energy processes in common envelope jets supernovae

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Abstract. We study high energy processes that occur during the merger of a neutron star (NS) or a black hole (BH) with the core of a red supergaint (RSG). The merger powers a luminous event termed common envelope jets supernova (CEJSN), that might account for lightcurves of peculiar transients. In the CEJSN scenario the NS/BH accretes mass from its surroundings through an accretion disk as it spirals-in inside the RSG's envelope and core. The compact object launches part of this mass as narrow jets that interact with their environment by depositing their kinetic energy in the envelope and core gas. These jets can serve as production sites of high energy neutrinos and r-process elements.

Keywords. neutrinos – binaries:general – stars:black holes – stars:jets – stars:massive – transients:supernovae

1. Introduction

The mergers of neutron stars (NSs) and black holes (BHs) with cores of red-supergiants (RSGs) are a subject of extensive research. These mergers might lead to bright transient events that are identified as peculiar supernovae (SNe) explosions. In the *common envelope jets supernova (CEJSN)* scenario for NS/BH-core mergers, a NS/BH is engulfed by an RSG star and spirals-in inside its envelope while accreting and expelling mass in the process. The mass is accreted through an accretion disk that launches two jets that propagate in opposite directions perpendicular to the orbital plane. The compact object eventually reaches the core and launches more energetic jets due to the high accretion rates in the dense core. The deposition of the jets' kinetic energy in the core drives bright transient events.

The most common formation channel of NS/BH core mergers, as Schrøder et al. (2020) and Grichener (2023) find, is as follows. Two massive main sequence (MS) stars in a binary system evolve independently from one another to begin with. At some point, when the initially more massive star is an RSG, mass transfer (either stable or unstable) from the RSG star to its MS companion strips the RSG of its envelope. The naked core keeps evolving and ends its life in a SN explosion, leaving a NS or BH remnant behind. If the system remains bound after the explosion, unstable mass transfer in the opposite direction might lead to a common envelop evolution in which the initially lighter star, which is in its RSG phase at this stage, swallows the compact object, leading to the CEJSN event described above.

Mergers of NS/BH with cores of RSGs might be associated with many peculiar transients. Thöne et al. (2011) suggest that the unusual gamma-ray burst 101225A originated from the merger of an helium star with a NS. Soker & Gilkis (2018) propose a CEJSN scenario to explain the enigmatic iPTF14hls transient. Soker et al. (2019) argue that CEJSNe can explain AT2018cow-like fast blue optical transients. Dong et al. (2021)

propose that merger-driven explosions are responsible for the luminous radio transient VT J121001+495647. Moreover, CEJSN with a NS companion can serve as the production site of heavy r-process elements, as suggested by Papish et al. (2015) and further developed by Grichener & Soker (2019), Grichener et al. (2022) and Grichener & Soker (2022).

In this work we focus on CEJSNe as emission sites of high energy neutrinos. We summarize the main results from Grichener & Soker (2021) in section 2. Then, we compare the properties of different CEJSN scenarios and summarize our results in section 3.

2. High energy neutrinos from common envelope jets supernovae: brief summary of Grichener & Soker (2021)

In Grichener & Soker (2021) we propose and explore a new astrophysical site for the formation and emission of the PeV neutrinos detected by IceCube in 2013 (see Aartsen et al. (2013) for the first observation of PeV-energy neutrinos with IceCube): CEJSN with a BH companion. When the BH is swallowed by an RSG it spirals-in inside its envelope and accretes mass through an accretion disk. The accretion disk launches jets in which high energy neutrinos can be formed. High energy cosmic rays can be scattered from the magnetic filed irregularities inside the jets. The cosmic rays then interact with photons that originate from the jet's head (the contact discontinuity between the reverse-shocked jet and the forward-shocked envelope) and form very energetic and short-lived pions. The charged pions decay to muons and then to electrons, emitting very energetic neutrinos that might be detected by IceCube. The neutral pions decay to gamma-rays. From kinematic considerations, the maximal energy of the high energy neutrinos formed in this process is about 20% of the maximal cosmic rays energy.

We use the stellar evolution code MESA (see Paxton et al. (2019) for the latest version) to evolve a $30M_{\odot}$ star with solar metallicity $Z_{\odot}=0.02$. During its RSG phase, when the star reaches a radius of $1000R_{\odot}$, we assume that it swallows a $3M_{\odot}$ BH that begins launching jets while spiralling-in inside the RSG envelope. We use sub-grid physics and mimic the effect of the jets on envelope by injecting the kinetic energy of the jets into the spherically symmetric stellar model. We then extract the density profiles of the extended RSG envelope to perform all the calculations presented in Grichener & Soker (2021).

We compute the maximum energy cosmic rays can reach by acceleration due to the jets' magnetic filed by comparing the typical acceleration timescale to typical cooling timescales. We find that the most relevant cooling process in our scenario is reduction in the protons' energies due to photohadronic interactions. As long as the acceleration timescale is shorter than the cooling timescale, the cosmic rays will keep gaining energy. By equating the acceleration timescale due to magnetic fields in the jets and the cooling timescale due to photohadronic interactions, we find that cosmic rays in our scenario can reach energies of

$$E_{\max} \approx 4\times 10^{16}\ \mathrm{eV}\left(\frac{\mathrm{B}'}{10^3\ \mathrm{G}}\right)\left(\frac{\mathrm{T}'_{\gamma}}{0.35\ \mathrm{keV}}\right)^{-3}\left(\frac{\Gamma}{100}\right), \qquad (2.1)$$

where B' is the magnetic filed in the rest frame of the jet, T'_{γ} is typical temperature of the photons that the cosmic rays interact with as measured in the rest frame of the jet and Γ is the Lorenz factor of the jets. This energy implies that CEJSN with BH companions might account for PeV neutrinos. For more details on the assumptions of our model, the computations we performed and other properties of high energy neutrinos and high energy neutrinos sites that the CEJSN scenario is compatible with please see Grichener & Soker (2021).

Table 1. Summary of the different common envelope jets supernova (CEJSN) scenarios. Based on Table 1 in Soker et al. (2019)

Scenario	Remnant companion	Description	Possible outcomes
CEJSN r-process[PSB15,GS19,GKS22,GS22]	NS	Common envelope evolution of the NS inside the core of the RSG; launching of neutron-rich jets	Heavy r-process nucleosynthesis
Prolonged CEJSN[SG18]	NS/BH	Common envelope evolution of the NS/BH inside the the RSG core; the core remains partly bound after the explosion causing prolonged accretion	iPTF14hls-like peculiar transients
Polar CEJSN[SGG19]	NS/BH	Common envelope evolution of the NS/BH in the RSG core; jets explode the core and eject relativistic polar outflow	AT2018cow-like fast blue optical transients
CEJSN neutrinos [GS21]	BH	Common envelope evolution of the BH inside the RSG envelope; launching of ultra-relativistic jets	Detectable PeV neutrinos
Thermonuclear CEJSN [GS23]	NS	The NS tidally-disrupts the core from the outside; thermonuclear ignition of the accretion disk mater	W49B-like supernova remnants

Refrences: GS19: Grichener & Soker (2019), GKS22: Grichener et al. (2022), GS21: Grichener & Soker (2021), GS22: Grichener & Soker (2022), GS23: Grichener & Soker (2023), PSB15: Papish et al. (2015), SG18: Soker & Gilkis (2018), SGG19: Soker et al. (2019).

3. Summary and discussion

CEJSN is a general name for a class of transients where a NS/BH merges with the core of an RSG star launching jets in the process. In the previous section we elaborated on the CEJSN scenario for high energy neutrino emission and briefly summarized the main findings of Grichener & Soker (2021). In Table 1 we present other CEJSN scenarios we developed over the years along their possible outcomes.

The main conclusion from this proceedings paper, and particularly from Table 1 is that CEJSN might account for several peculiar transients and high energy astrophysical phenomena, which emphasizes the need for more extensive studies in the field.

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