PRE-SUPERNOVA OUTBURSTS OF MASSIVE STARS IN THE PRESENCE OF A NEUTRON STAR COMPANION

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ABSTRACT

We study the pre-explosion outbursts (PEOs) of massive stars that might result from a rapid expansion of the massive star in the presence of a close companion. We assume that activity in the core of the massive star about two years before explosion energizes the envelope, and with the stellar evolutionary code MESA follow the inflated envelope as a result of energy deposition to the envelope. We examine the conditions for a companion star to accrete mass from the inflated envelope. We find that for the general conditions that we assume, bright PEOs require a neutron star companion at an orbital separation of \( \approx 1000 - 2000R_\odot \). We assume that the mass-accreting neutron star launches jets. These jets shape the circumstellar matter to highly non-spherical structures, such that the explosions of core collapse supernovae (CCSNe) that follow PEOs might lack an axial (cylindrical) symmetry. In some case main sequence star companions can also energize PEOs, but much weaker ones. This study adds another scenario by which neutron stars can power PEOs. Another scenario is the common envelope jets supernova (CEJSN) impostor where a neutron star enters the envelope of the massive star.

1. INTRODUCTION

Some massive stars undergo pre-explosion outbursts (PEOs) tens of years to days before they terminate explode as a core collapse supernova (CCSN; e.g., Foley et al. 2007; Pastorello et al. 2007; Smith et al. 2010; Mannheim et al. 2013; Ofek et al. 2013; Pastorello et al. 2013; Margutti et al. 2014; Ofek et al. 2014; Svirski & Nakar 2014; Fraser et al. 2015; Moriya et al. 2015; Goranskij et al. 2016; Ofek et al. 2016; Tartaglia et al. 2016; Boian & Groh 2017; Margutti et al. 2017; Liu et al. 2017; Nyholm et al. 2017; Pastorello et al. 2017; Yaron et al. 2017). The outburst is accompanied by mass ejection that forms a dense circumstellar matter (CSM). After explosion the supernova ejecta collides with the CSM, burning kinetic energy to radiation. Some of the PEOs are observed to be non-spherical. Reilly et al. (2017) deduce from their spectropolarimetric observations of the 2012 PEO of SN 2009ip, that was a major outburst of a luminous blue variable (LBV), that the CSM that was formed from the PEO is compatible with a disk-like geometry. In some cases enhanced mass loss rate episodes might occur as early as the core carbon-burning phase (e.g., Moriya et al. 2014; Margutti et al. 2017).

Since standard stellar evolutionary simulations do not lead to PEOs, researchers have introduced extra mechanisms to trigger and power PEO of CCSNe. Some mechanisms attribute the instability to the envelope of the massive star, such as the radiation-driven instabilities (e.g., Blaes & Socrates 2003) that might occur in some LBVs (e.g., Kiriakidis et al. 1993; Kashi et al. 2016). Other mechanisms start from the very high power of the nuclear burning in the core that triggers vigorous core convection. Energy that is carried from the convective zones to the envelope, e.g., by waves (Quataert & Shiode 2012; Shiode & Quataert 2014) causes the envelope to either eject mass (e.g., Quataert & Shiode 2013; Shiode & Quataert 2014), or to expand (Soker 2013; Shiode & Quataert 2014; Smith & Arnett 2013). In some cases enhanced mass loss rate episodes might occur as early as the core carbon-burning phase (e.g., Moriya et al. 2015; Soker 2013; Mcley & Soker 2014). We do emphasize that even PEO binary models require that the massive star first experiences...
some kind of unstable phase that triggers a strong binary interaction.

Mcley & Soker (2014) run the stellar evolutionary code MESA and find that energy deposited to the envelope is likely to lead to its expansion rather than to large mass ejection (also Fuller 2017). We here continue their study and calculate the properties of the possible binary companion that can accrete mass, and the energy that the companion might release by the accretion process from the inflated envelope. We find that for the specific instability we use for the primary star a very energetic outburst requires the companion to be a neutron star (NS), and hence in this study we consider mainly a NS companion.

In section 2 we describe the inflation of the envelope because of the energy we inject into it. In section 3 we examine the possible mass of the companion as function of orbital separation, and in section 4 we estimate the accretion power of the companion during the pre-explosion outburst. In section 5 we study the case of an expanding shell that might be powered in part by a companion. We summarize in section 6.

2. ENVELOPE INFLATION

We run the stellar evolution code MESA (version 10000: Paxton et al. 2011, 2013, 2015) and follow the evolution of a star with an initial mass of $M_{1,0} = 15M_\odot$ and metallicity of $Z = 0.02$. Just before core collapse the mass of the star is $M_1 = 13.55M_\odot$ and its radius is $R_1 = 861R_\odot$.

To mimic core activity that powers the envelope, by waves or by magnetic activity, we inject energy to the envelope. The energy injection scheme is similar, but not identical to that of Mcley & Soker (2014). About two years before core collapse we start to inject energy with a power of $L_{\text{wave}} = 3.2 \times 10^6 L_\odot$, which is much more than the stellar luminosity at that stage, $L = 8.1 \times 10^4 L_\odot$. We inject the energy inside one numerical shell at the driven radius $r_d$ where the wave luminosity equals the maximum luminosity that can be carried by convection $L_{\text{wave}} = L_{\text{max,conv}}(r_d)$. The maximum energy that can be carried by convection is $L_{\text{max,conv}} = 4\pi \rho r^2 c_s^3$, where $c_s$ is the local sound speed and $\rho$ is the density. We then follow the structure of the inflated envelope.

We start to inject energy at an age of $1.2704215 \times 10^7$ yr which we take as $t = 0$, and end it at $t = 2.3$ yr (an age of $1.27042173 \times 10^7$ yr). The envelope inflates from an initial radius of $R_1 = 861R_\odot$ to a large radius as we present in Fig. 1. In Fig. 2 we present the density at six different radii, all were outside the star before inflation started.

3. THE COMPANION

To survive outside the envelope of the primary star the secondary star should obey two conditions as follows. (1) Not to be too massive to cause the primary star to overflow its Roche lobe. (2) Be massive enough to maintain Darwin stability against rapid spiraling-in evolution towards the primary envelope.

The effective radius of the Roche lobe of the primary star, as we take from Eggleton (1983), should obey

$$R_L = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln (1 + q^{1/3})} a > R_1(t = 0),$$

where $q = M_1/M_2$ in this case. In our single star evolutionary model $R_1 = 861R_\odot$ just before the inflation phase, and $M_1 = 13.55M_\odot$. Condition (1) implies that the system should be below the blue line in Fig. 3.

The moment of inertia of the star when we start the energy injection is $I_1 = 1.4 \times 10^6 M_\odot R_\odot^2$. Darwin stability, i.e., stability against a rapid spiraling-in process, reads

$$M_2 > \frac{3I_1(M_1 + M_2)}{M_1a^2} = \frac{I_1}{1.4 \times 10^6 M_\odot R_\odot^2} \left(\frac{a}{1000R_\odot}\right)^{-2} \frac{M_1 + M_2}{M_1} M_\odot$$

Condition (2) implies that the system should be above the red line in Fig. 3. Another condition for the companion to accrete mass is that it will be within the radius of the inflated envelope. In the present case this is $a < 1690R_\odot$, as marked by the vertical line in Fig. 3. The allowed region in the mass-
Bondi-Hoyle-Lyttleton accretion rate is given by
\[ \dot{M}_2 = \pi M_2^2 \left( \frac{2GM_2}{v_{\text{r}}^2} \right)^2 = 0.08 \left( \frac{\rho}{10^{-9} \text{ g cm}^{-3}} \right) \left( \frac{M_1 + M_2}{1.4M_\odot} \right)^{3/2} \left( \frac{a}{1500R_\odot} \right)^{3/2} M_\odot \text{ yr}^{-1}. \]  

We take the scaling of the density according to the results presented in Fig. 2.

The accretion rate as given by equation (3) is about two orders of magnitude above the threshold for neutrino cooling to operate \(10^{-3} M_\odot \text{ yr}^{-1}\); Houck & Chevalier 1991), and hence such an accretion rate is allowed despite being upper Eddington according to the usual definition. Consider that the NS accretes less than this value and power the inflated envelope with an energy of about \(\eta_p \simeq 0.1 - 0.01\) times the accretion at the BHL accretion rate. For an accretion phase that lasts for about one month, \(t_{\text{acc}} \simeq 0.1\) yr, from the moment the inflated envelope reaches the secondary to explosion (see Fig. 2), the total pre-explosion accretion energy liberated by the NS, as jets and radiation, is
\[ E_{\text{acc}} \simeq 10^{50} \left( \frac{\eta_p}{0.1} \right) \left( \frac{M_2}{0.08M_\odot \text{ yr}^{-1}} \right) \left( \frac{t_{\text{acc}}}{0.1 \text{ yr}} \right) \text{ erg.} \]  

We point to the following properties of the proposed interaction. (1) Most of the accretion energy is carried by neutrinos. Most of the rest by jets. Radiation carries negligible amount from near the NS as the inflow is optically thick. It is possible that the energy carried by the jets is only \(\approx 10^{49}\) erg for the scaling we use here. (2) As the jets collide with the inflated envelope and after the envelope gets back inside its Roche lobe, some kinetic energy is converted to radiation and the process becomes visible. (3) Since the inflated envelope grows to only about several times the initial radius of the star, the constraints on the companion are such that a NS will make the largest effect. (4) The interaction time is much shorter than the orbital time. The outcome of the interaction will be highly distorted, as the jets that the NS launches will expel the inflated envelope from one side only. The ejecta from the explosion that follows will interact with highly distorted inflated envelope and/or a shell. Such a geometry should be considered when fitting light curve of some CCSNe that are preceded by PEOs.

5. SHAPING AN EXPANDING SHELL

An accretion from an inflated envelope is not the only way to form a pre-explosion transient by a mass-accreting companion. Consider the model that Rest et al. (2018) present for the fast-evolving luminous transient KSN 2015K. In that model a massive star at the end of its evolution lost a mass of \(M_{\text{CSM}} = 0.15M_\odot\) that at the time of explosion was a CSM shell with a radius of \(R_{\text{CSM}} = 4 \times 10^{14} \text{ cm}\) and a width of \(\Delta R_{\text{CSM}} = 1 \times 10^{14} \text{ cm}\). The supernova ejecta in that model has a mass of \(M_{\text{ej}} = 10M_\odot\), a velocity of \(v_{\text{ej}} = 8500 \text{ km s}^{-1}\), and a kinetic energy of \(E_{\text{ej}} = 7 \times 10^{51}\). We note that neutrino-driven explosion cannot supply this energy (e.g. Ebinger et al. 2018), and most likely this supernova was exploded by jets, as we think all CCSNe are (e.g. Soker & Gilkis 2017a).

Let us consider such a shell ejection in a case where a NS companion orbits the supernova progenitor. If such a CSM shell is ejected at the escape speed from the surface of the primary star \(v_{\text{CSM}} = (2GM_1/R_1)^{1/2}\), and the companion is not too close to the surface, then the relative velocity of the shell and the companion is \(v_{\text{r}} \simeq v_{\text{CSM}}\). The fraction of the mass that is accreted by the secondary star is \(f_{\text{acc}} \simeq \pi R_{\text{acc}}^2/4\pi a^2\), where \(R_{\text{acc}}\) is the accretion radius and \(a\) is the orbital separation. We find for the accreted mass

\[ M_{\text{acc-CSM}} \simeq \frac{1}{4} \left( \frac{M_2}{M_1} \right)^2 \left( \frac{R_1}{a} \right)^2 \frac{M_{\text{CSM}}}{0.15M_\odot} = 4 \times 10^{-5} \left( \frac{M_2}{0.1M_1} \right) \frac{a}{3R_1}^{-2} \left( \frac{M_{\text{CSM}}}{0.15M_\odot} \right) M_\odot. \]  

Rest et al. (2018) consider two possibilities, that the star
was a giant or that it was a hydrogen poor progenitor with a radius of no more than several solar radii. In the first case the shell velocity is \( v_{\text{CSM}} \approx 100 \text{ km s}^{-1} \) and in the second it is \( v_{\text{CSM}} \approx 1000 \text{ km s}^{-1} \). The accretion phase lasts for a time of 

\[
t_{\text{acc-CSM}} \approx 0.3 \left( \frac{\Delta R_{\text{CSM}}}{10^{14} \text{ cm}} \right) \left( \frac{v_{\text{CSM}}}{100 \text{ km s}^{-1}} \right)^{-1} \text{ yr. (6)}
\]

**Stripped-envelope supernova progenitors.** For a hydrogen deficient progenitor of a small radius the duration will be 10 times shorter than that given by equation (6) about 0.03 yr. For the parameters used in equation (6) the accretion rate onto a NS close to a small massive star would be above \( 10^{-3}M_\odot \text{ yr}^{-1} \), hence neutrino cooling is efficient. Let us take the fraction of accretion energy on to the NS that goes into radiation, directly or first to kinetic energy and then radiation, to be \( \eta_p = 0.1 \). For the parameters used in equation (6) we find the emitted radiation to be \( E_{\text{rad-CSM}} \approx 10^{48} \eta_p /0.1 \text{ erg} \). The accretion phase lasts for about two weeks for the above parameters. In a case of a NS at a separation of \( < 100R_\odot \), the typical optical depth of a spherical shell is huge and the expansion time is short, and hence only a small fraction of the energy will escape as radiation. However, the energy carried by the jets, \( E_{\text{jets,NS}} \approx \times 10^{47} \text{ erg} \) if about ten percent of the accreted mass is ejected in jets at the escape speed from a NS, is of the order of ten per cent of the kinetic energy of the shell \( E_{\text{CSM,1000}} \approx 1.5 \times 10^{48} \text{ erg} \) for the parameters used here and a shell velocity of \( v_{\text{CSM}} = 1000 \text{ km s}^{-1} \). The jets will open two opposite small lobes (‘ears’), along which the optical depth will be much lower. We might then have a transient event. Since the radius is small, it will be a blue event lasting for about days to weeks. If about ten per cent of the kinetic energy of the jets is transferred to radiation, the typical luminosity of the event would be \( L_{\text{rad-CSM}} \approx 10^{40} - 10^{41} \text{ erg s}^{-1} \).

**Giant progenitors.** Let us then consider a massive giant star of a radius of \( \approx 2 - 4 \text{ AU} \) that ejects such a shell at a velocity of \( \approx 100 \text{ km s}^{-1} \). The accretion rate according to the parameters used here is \( \approx 10^{-4}M_\odot \text{ yr}^{-1} \). This does not allow an efficient neutrino cooling. But if we consider a somewhat denser shell and/or more massive one, and the jets can also carry energy out of the accretion flow (e.g., Chamandy et al. 2018 for a main sequence star of a white dwarf accretor), then we might consider an accretion at this accretion rate on to a NS. The radiation diffusion time and expansion time are of the order of several months. Over all, the outcome might be a transient event lasting several months with a typical luminosity of \( L_{\text{rad-CSM}} \approx 10^{40} \text{ erg s}^{-1} \), for the parameters use here and for \( \eta_p = 0.1 \), but the luminosity be higher at maximum.

A comment is in place here. Consider the formation of the shell in the model of Rest et al. (2018) in the case of a giant. The shell was ejected \( \approx 4 \times 10^{14} \text{ cm}/v_{\text{CSM}} \approx 1.3 \text{ yr} \) before explosion. Consider a case where there is no NS companion, but rather a main sequence companion instead of a NS. If the envelope is inflated as in our study in section 2 but for a longer duration of several years, then a companion of \( 2M_\odot \) at an orbital separation of \( \approx 1600R_\odot \) could have accreted mass from the inflated envelope during the inflation time of about one year a mass of \( \approx 0.1M_\odot \) (see equation 5). If about 10 per cent of this mass is ejected in jets at the escape speed from the main sequence star, then the jets carry an energy of \( E_{\text{jets}} \approx 10^{46} \text{ erg} \). The kinetic energy of the shell is \( E_{\text{CSM,100}} \approx 1.5 \times 10^{46} \text{ erg} \) for a shell velocity of \( v_{\text{CSM}} = 100 \text{ km s}^{-1} \). This implies that if the shell in the model studied by Rest et al. (2018) was ejected by a giant, it could have been powered by a main sequence binary companion (e.g., McLay & Soker 2014).

### 6. SUMMARY

We examined some aspects of the binary scenario for PEOs. We inflated an envelope of a giant star about two years before core collapse by injecting energy to the envelope (section 2). This energy injection mimics the effect of waves or magnetic activity from the core of the pre-collapse star (section 1).

We found that for the general conditions that we have used, bright PEOs that occur months before explosion require a NS companion at an orbital separation of \( \approx 1000 - 2000R_\odot \). At larger separations the accretion rate is too low or does not exist, while for much shorter separations the orbit is unstable (Fig. 3). The constraints on the companion mass (green area in Fig. 3) allow for a NS. Because of the low density of the inflated envelope (Fig. 2), only mass accretion on to a NS can lead to a very energetic PEO.

Based on preliminary simulations we estimate that a treatment with consistent binary evolution increases the parameter space allowed for the orbital separation and mass of the companion, particularly if the star is smaller. The star might be smaller if the companion removes large amount of mass from its envelope for example (e.g., the progenitor of SN 1987A). This is the subject of a future study.

We assume that the event is energized by jets that the mass-accreting NS launches for a time period of about weeks to months. The jets collide with the inflated envelope and after they exit the inflated envelope they interact with the older wind. This interaction converts kinetic energy to radiation.

As the jet-launching episode lasts for a time shorter than the orbital time in the cases we studied, the jets distort the inflated envelope and the CSM. The explosion will lose spherical symmetry and axial symmetry after the shock breaks out from the inflated envelope. The explosion of CCSNe that follow PEOs might lack an axial (cylindrical) symmetry.

Main sequence star companions can also energize PEOs, but much weaker ones. The typical energy of the jets can be \( E_{\text{jets,MS}} \approx 10^{46} \text{ erg} \) for the typical parameters that we use in this study (section 5) rather than \( E_{\text{jets,NS}} \approx 10^{48} - 10^{49} \text{ erg} \) for NS companions (section 4). Such jets can shape the CSM of CCSNe. In section 5 we discussed the possibility that a main sequence companion accretes mass from an inflated envelope and launches jets that influence the structure of an expanding shell. The shell in the model of Rest et al. (2018) for the fast-evolving luminous transient KSN 2015K could have been shaped by such jets.

This study adds to the cases where NS can power PEOs. Gilkis et al. (2018) discuss the case where a NS enters the envelope itself and power a very strong out-
burst, termed a common envelope jets supernova (CE-JSN) impostor.

The main findings of this study is that companions, in particular NS companions, but not only NS, can energize PEOs and shape the CSM to acquire highly asymmetrical structure lacking even axisymmetrical geometry.

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