Ejecting the envelope of red supergiant stars with jets launched by an inspiraling neutron star

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ABSTRACT

We study the properties of the jets launched by a neutron star spiraling inside the envelope and core of a red supergiant (RSG) star, and find that Thorne-Żytkow objects (TZO) cannot be produced via a common envelope (CE) evolution. We use the jet-feedback mechanism, where energy deposited by the jets drives the ejection of the entire envelope and part of the core, and find a very strong interaction of the jets with the core material at late phases of the CE evolution. Following our results we speculate on two rare processes that might take place in the evolution of massive stars. (1) In recent studies it was claim that the peculiar abundances of the HV2112 RSG star can be explained if this star is a TZO. We instead speculate that the rich-calcium envelope comes from a supernova explosion of a stellar companion that was only slight more massive that HV2112, such that during its explosion HV2112 was already a giant that intercepted a relatively large fraction of the SN ejecta. (2) We raise the possibility that strong r-process nucleosynthesis, where elements with high atomic weight of $A > 130$ are formed, occurs inside the jets that are launched by the NS inside the core of the RSG star.

1. INTRODUCTION

Massive stars, in particular if in interacting binary systems, hold many secrete in their evolution. Some of these puzzles are related to the synthesis of different isotopes. Our study is related to the peculiar abundances of some isotopes in the red supergiant (RSG) star HV2112 in the Small Magellanic Cloud, and to the site of the strong r-process. The paper is centered around jets that are assumed to be launched by the NS as it accretes material from the common envelope (CE) with a RSG star.

Contrary to recent claims that HV2112 is a Thorne-Żytkow objects (TZO: \textsuperscript{[Levesque et al. 2014; Tout et al. 2014]}), we will show that a TZO is unlikely to be formed through the evolution of

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a neutron star (NS) inside the envelope of a RSG star. The reason is that the jets launched by the NS expel the entire envelope and most of the core.

Another major problem in astrophysics is the exact sites where the r-process nucleosynthesis takes place. For the site(s) of the “strong r-process”, where elements of atomic weight $A \gtrsim 130$ are formed, there have been two main contenders in recent years (e.g., Thielemann et al. 2011), the merger of two neutron stars (e.g., Qian 2012; Rosswog et al. 2013, and references therein), and jets from rapidly rotating single newly born NS (Winteler et al. 2012).

Previous studies of r-process nucleosynthesis in jets include Cameron (2001) who suggested the possibility of creating r-process elements inside the jets launched at a velocity of $\frac{1}{2}c$ from an accretion disk around a rapidly rotating proto NS. Nishimura et al. (2006) simulated the r-process nucleosynthesis during a jet powered explosion. In their simulation a rotating star with a magnetic field induces a jet-like outflow during the collapse which explode the star. Neutrinos play no role in their simulation. Papish & Soker (2012) calculated the nucleosynthesis inside the hot bubble formed in the jittering-jets model for core-collapse supernova explosions, and found that substantial amount of r-process material can be formed. Papish & Soker (2012) assumed that in the jittering-jets explosion model the jets are launched close to the NS where the gas is neutron-rich (e.g., Kohri et al. 2005).

Some r-process elements are believed to be found in all low-metallicity stars, and thus r-process nucleosynthesis must take place continuously from very early in the Galactic evolution (Sneden et al. 2008). Since the jittering-jets model was constructed to account for the explosion of all core collapse supernovae (CCSNe), the r-process induced by the jittering jets can account for the continuous formation of r-process elements. However, the abundance of heavy r-process elements has much larger variations among different stars, implying that part of the heavy r-process, termed strong r-process, is formed in rare events (Qian 2000; Argast et al. 2004).

Here we propose a new speculative site for strong r-process nucleosynthesis which is formed by jets launched by a NS spiraling-in inside the core of a giant star. These jets will also explode the star. This is a rare evolutionary route and hence complies with the finding of large variations in the abundances of these elements. In this first study we limit ourselves to present the scenario and show its viability. Most ingredients of our newly proposed scenario were studied in the past but were never put together into a coherent picture to yield a new possible site for the strong r-process site. Previously studied ingredients of our proposed scenario include the CE of a NS and a giant (Thorne & Zytkow 1975; Chevalier 2012), the launching of neutron-rich gas from accretion disks around compact objects (e.g., Surman & McLaughlin 2004; Kohri et al. 2005), the launching of jets by NS accreting at a high rate (Fryer et al. 1996), and the formation of r-process elements in jets from NS (Fryer et al. 2006). The idea that jets can explode the star, in a CE (Chevalier 2012) and rapidly rotating single stars (e.g. LeBlanc & Wilson 1970;
Meier et al. 1976; Bisnovatyi-Kogan et al. 1976; Khokhlov et al. 1999; MacFadyen et al. 2001; Woosley & Janka 2005; Couch et al. 2009), was also studied in the past. However, we claim that all CCSNe are explode by jets, the jittering-jets model, that also synthesis r-process elements (but not the strong r-process), and hence our newly proposed scenario is part of a unified picture we try to construct for exploding all massive stars and the synthesis of r-process elements.

Taam et al. (1978) already studied the spiraling-in of a NS inside a red supergiant envelope and considered two outcomes, that of envelope ejection and of core-NS merger. However, they did not consider jets. The removal of the envelope during a CE evolution by jets launched by a NS or a WD companion was discussed by Soker (2004). Chevalier (2012) explored the possibility that the mass loss prior to an explosion of a core-NS merger process is driven by a CE evolution of a NS (or a BH) in the envelope of a massive star. Jets launched by an accretion disk around the NS companion deposit energy to the envelope and explode the star, much as in Soker (2004). However, for NS the accretion process to form an accretion disk is much more efficient due to neutrino cooling (Houck & Chevalier 1991; Chevalier, 1993, 2012). This allows the NS to accrete at a very high rate, much above the classical Eddington limit, hence leading to an explosive deposition of energy to the envelope (Chevalier, 2012). The process by which jets launched by an inspiraling NS expel the envelope (Soker, 2004) and then the core (Chevalier, 2012) implies that no Thorne-Żytkow objects (Thorne & Zytkow 1975; a red giant with a NS in its core) can be formed via a CE evolutionary route. We strengthen this conclusion in section 2.

In section 2 we study the CE evolution toward the explosion and estimate the typical accretion rate and time scale. A new ingredient in our CE calculation is the assumption that mainly jets launched by the inspiraling NS drive the envelope ejection via the jet-feedback mechanism (Soker 2004; Soker et al. 2013; Soker 2014). It is possible that the NS will expel the entire envelope by the jets (Soker, 2004), and will not enter the core. However, it seems that merger at the end of the CE phase can be quite common (Soker, 2013), and we study such cases. In section 3 we list two, somewhat speculative, processes that are motivated by our results. Our summary is in section 4.

2. JETS INSIDE A COMMON ENVELOPE

2.1. General derivation

The Bondi-Hoyle-Lyttleton (BHL) mass accretion rate inside the envelope is (e.g., Armitage & Livio 2000; for a general overview of CE see Ivanova et al. 2013)

$$\dot{M}_{\text{BHL}} = \pi \left( \frac{2GM_{\text{NS}}}{v_r^2 + c_s^2} \right)^2 \rho_e \sqrt{v_r^2 + c_s^2},$$  \hspace{1cm} (1)
where $M_{\text{NS}}$ is the NS mass, $v_r$ its velocity relative to the giant’s envelope, $c_s$ is the sound speed inside the envelope, and $\rho_e$ is the envelope density at the NS location. The NS moves mildly supersonically and we can use the approximation $\sqrt{v_r^2 + c_s^2} \approx v_K$, where $v_K$ is the NS’s Keplerian velocity.

We use the red giant’s profile from $\text{Taam et al. (1978)}$ with a mass of $M_g = 16 M_\odot$, a radius of $R_g = 535 R_\odot$, a core radius of $R_{\text{core}} = 2.07 \times 10^{10}$ cm, and a core mass of $M_{\text{core}} = 7 \times 10^{33}$ g $\approx 3.5 M_\odot$. A power law fit of the density profile in the giant’s envelope gives

$$\rho_e \simeq A r^{\beta} = 0.68 \left( \frac{r}{R_\odot} \right)^{-2.7} \text{g cm}^{-3}, \quad (2)$$

where $r$ is the radial coordinate of the star. The BHL accretion rate can then be written as

$$\dot{M}_{\text{BHL}} \simeq \pi \left( \frac{2GM_{\text{NS}}}{v_K^2} \right)^2 \rho_e v_K = 4\pi a^2 \left( \frac{M_{\text{NS}}}{M(a)} \right)^2 \rho_e v_K \simeq 3 \times 10^3 \left( \frac{a}{1R_\odot} \right)^{-1.2} \left( \frac{M(a)}{7M_\odot} \right)^{-3/2} M_\odot \text{yr}^{-1}, \quad (3)$$

where $a$ is the distance between the NS and the core’s center, $M_g(r) = M_{\text{core}} + M_{\text{env}} (r/R_g)^{0.3}$ is the giant’s mass enclosed inside radius $r$, $M(r) = M_g(r) + M_{\text{NS}}$, and we will take $M_{\text{NS}} = 1.4 M_\odot$ in the rest of the paper. We take the mass accretion rate to be a fraction $f_a$ of the BHL accretion rate, and we take a fraction $\eta \simeq 0.1$ of the accreted mass to be launched in the two jets

$$\dot{M}_{2j} = \eta \dot{M}_{\text{acc}} = \eta f_a \dot{M}_{\text{BHL}}. \quad (4)$$

Around the NS an accretion disk is easily formed as the ratio of orbital separation to the NS radius is very large, such that the specific angular momentum of the accreted gas is more than an order of magnitude above what is required to form an accretion disk (eq. 7 in $\text{Soker (2004)}$). Such an accretion disc can launch two bipolar jets inside the envelope as shown schematically in Fig. 1. As a result of the NS motion the jets will encounter different parts of the envelope during their propagation and form a hot bubble on each side of the orbital plane ($\text{Soker et al. (2013)}$).

To examine the fate of the jets we compare the propagation time scale of the jets inside the envelope $\tau_j$ with the time scale it takes for a jet’s head to cross its width $\tau_c$. $\tau_j$ can be estimate as follows. The jets’ head velocity $v_h$ is determined by the pressure balance on the two sides of the jets’ head $\rho_e v_h^2 \simeq \rho_j (v_j - v_h)^2 \simeq \rho_j v_j^2$, as $v_h \ll v_j$; $v_j$ is the initial velocity of the gas in the jet and $\rho_e$ is the envelope density encountered by the jet. We take the jet to have a half opening angle of $\theta \sim 0.2$ and a mass outflow rate into each jet of $\frac{1}{2} \eta \dot{M}_{\text{acc}}$. The jets’ head velocity is then

$$v_h(z) \simeq v_j \sqrt{\frac{\rho_j}{\rho_e(z)}} = \sqrt{\frac{\frac{1}{2} \eta \dot{M}_{\text{acc}} v_j}{\pi z^2 \theta^2 A(a^2 + z^2)^{3/2}}}, \quad (5)$$
where we take the jets’ density to be
\[ \rho_j = \frac{1}{2} \frac{\eta \dot{M}_{\text{acc}}}{\pi z^2 \theta^2 v_j}, \] (6)
as \( \theta \ll 1 \). The propagation time of the jets to a distance \( z = \int_0^\tau_j v_h dt \) can then be solved analytically
\[ \tau_j = \frac{a^{2+\beta/2}}{2 + \beta/2} \theta \sqrt{\frac{2A\pi}{\eta \dot{M}_{\text{acc}} v_j}} \left[ \left(1 + \frac{z^2}{a^2}\right)^{1+\beta/4} - 1 \right]. \] (7)

We substitute for \( \dot{M}_{\text{acc}} \) from equation 4, take \( \beta = -2.7 \), define \( v_{j5} \equiv v_j/10^5 \) km s\(^{-1} \), and scale quantities for the inner part of the envelope to get
\[ \tau_j \simeq 3 \times 10^3 v_{j5}^{-1/2} \left( \frac{a}{R_\odot} \right)^2 \left( \frac{\theta}{10^\circ} \right)^{1/2} \left( \frac{\eta}{0.1} \right)^{-1/2} \times \left( \frac{M_{\text{NS}}}{1.4M_\odot} \right)^{5/4} \left[ \left(1 + \frac{z^2}{a^2}\right)^{1+\beta/4} - 1 \right] \text{s.} \] (8)

For the crossing time we take (Soker 2004)
\[ \tau_c = \frac{2z\theta}{v_K} \simeq 200 \left( \frac{\theta}{10^\circ} \right) \left( \frac{z}{R_\odot} \right) \left( \frac{a}{R_\odot} \right)^{1/2} \left( \frac{M(a)}{7M_\odot} \right) \text{s.} \] (9)

The ratio between these times is given by (note that \( \theta \) cancels out)
\[ \frac{\tau_j}{\tau_c} \simeq 15 v_{j5}^{-1/2} \left( \frac{a}{R_\odot} \right)^{1/2} \left( \frac{\eta}{0.1} \right)^{-1/2} \times \left( \frac{M_{\text{NS}}}{1.4M_\odot} \right)^{1/4} \left[ \left(1 + \frac{z^2}{a^2}\right)^{1+\beta/4} - 1 \right]. \] (10)
The jets will not be able to penetrate through the envelope when \( \tau_c < \tau_j \). For \( z \sim a, \beta = -2.7 \) and \( \eta = 0.1 \) the ratio is

\[
\frac{\tau_j}{\tau_c} \simeq 4 \left( \frac{a}{R_\odot} \right)^{1/2}.
\]  \( (11) \)

We find that the condition \( \tau_c < \tau_j \) is satisfied. We conclude that the jets will not be able to penetrate through the envelope and will deposit their energy inside the envelope.

The total energy deposited by the jets inside the envelope is

\[
E_j = \int \dot{E}_j dt = \int \frac{1}{2} \dot{M}_{\text{acc}} v_j^2 dt.
\]  \( (12) \)

\( \dot{M}_{\text{acc}} \) can be eliminated by using an expression that equates the power of the interaction of the NS with the envelope, i.e., the work of the drag force, with the releasing rate of orbital energy [Iben & Livio 1993]

\[
- \frac{GM_g(a)M_{\text{NS}}}{2a^2} \dot{a} = \xi \dot{M}_{\text{BHL}} v_k^2,
\]  \( (13) \)

where \( \xi \simeq 1 \) is a parameter characterizing the drag force (accretion + gravitational interaction with the rest of the envelope). Equations \((12)\) and \((13)\) give

\[
\int dE_j = - \int \frac{1}{4a} \frac{\eta f_a M_g(a)M_{\text{NS}}}{M(a)} v_j^2 da.
\]  \( (14) \)

Approximating the reduced mass by \( M_g(a)M_{\text{NS}}/M(a) \simeq M_{\text{NS}} \) allows us to perform the integration analytically to obtain

\[
E_j \simeq \frac{1}{4} \frac{\eta f_a}{\xi} v_j^2 M_{\text{NS}} \left[ \ln \left( \frac{R_k}{a} \right) \right].
\]  \( (15) \)

As the jets don’t penetrate the envelope, we assume that there is a self regulation process, i.e., a negative feedback process [Soker et al. 2013], such that the jets from the NS prevent too high accretion rate onto the NS.

### 2.2. Inside the envelope

Let the removal of the envelope by the jets have an efficiency of \( \chi \), such that

\[
\chi E_j \lesssim E_{\text{e/bind}}.
\]  \( (16) \)

The removal energy supplied by the jets is smaller than the binding energy of the envelope as in addition to the energy deposited by the jets there is the orbital energy of the spiraling-in binary
system. In the traditional CE calculation only the orbital energy is considered. The binding energy of the envelope of the model described in section 2 is

\[ E_{\text{bind}} \simeq \frac{G M_{\text{env}}^2}{R_{\text{core}}} \left\{ \frac{3 M_{\text{core}}}{7 M_{\text{env}}} \left( \frac{R_{\text{core}}}{R_g} \right)^{0.3} + \frac{3}{4} \left( \frac{R_{\text{core}}}{R_g} \right)^{0.6} \right\}. \]  

(17)

For \( R_{\text{core}} \simeq 0.3 R_\odot \), \( M_{\text{core}} = 3.5 M_\odot \) and \( M_{\text{env}} = 12.5 M_\odot \) we obtain \( E_{\text{bind}} \simeq 4 \times 10^{49} \text{ erg} \). Substituting equations (15) and (17) in equation (16) gives

\[ f_a \sim 0.01 \xi \left( \frac{\eta}{0.1} \right)^{-1} \left( \frac{\chi}{0.01} \right)^{-1}. \]  

(18)

Substituting typical values in equation (3) with \( \chi \simeq 0.01 \) we find the accretion rate of the NS for \( a \sim 1 R_\odot \) to be \( \sim 30 M_\odot \text{ yr}^{-1} \). In this regime neutrino-cooled accretion occurs as \( \dot{M}_{\text{acc}} \gtrsim 10^{-3} M_\odot \text{ yr}^{-1} \) (Chevalier 1993), and so high accretion rate can take place. The Keplerian orbital time is \( P_K \sim 1 (a/R_\odot)^{3/2} \) hours. If evolution proceed over a time of \( 10 P_K \simeq 0.5 \text{ day} \), the total accreted mass is \( \lesssim 0.04 M_\odot \).

The total accreted mass in the jet-feedback scenario is calculated from

\[ \frac{E_{\text{bind}}}{\chi} \simeq E_j \simeq \frac{\eta}{2} \dot{M}_{\text{acc}} v_j^2. \]  

(19)

This gives an upper limit on the accreted mass as the orbital gravitational energy released by the NS-core system reduces the required energy from the jets. Substituting typical values used here we derive

\[ M_{\text{acc}} \lesssim 0.04 v_j^{-2} \left( \frac{E_{\text{bind}}}{4 \times 10^{49} \text{ erg}} \right) \left( \frac{\eta}{0.1} \right)^{-1} \left( \frac{\chi}{0.01} \right)^{-1} M_\odot. \]  

(20)

This is the same as the value estimated above, showing that the final stage of the CE inside the envelope lasts for \( \sim 1 \text{ day} \). Hence, most of the accretion takes place during the few hours to few days of the final stage of the CE, when evolution is rapid. In the outer regions of the envelope, that have very small binding energy and where the spiraling-in time is of order of years, the accretion rate is negligible in the feedback scenario.

We conclude that within the frame of the jet-feedback mechanism a NS ends the spiraling-in inside the envelope of a giant after accreting only a small amount of mass, that most likely leaves it as a NS rather than forming a BH.

### 2.3. Inside the core

We can repeat the calculations of section 2.2 to the phase when the NS is inside the core. The Keplerian orbital period for the core and the NS is \( \sim 10 \text{ min} \). During that time the NS can explode
the core with the jets. The explosion will last few minutes, but since the entire systems is optically thick due to the ejected envelope, the explosion will last days, as in a typical SN. The binding energy of the core is $> 10^{50}$ erg. The ejected mass in the jets in the frame of the jet-feedback mechanism is

$$M_{2j} = \eta M_{\text{acc}} \lesssim 0.01 v_{j5}^{-2} \left( \frac{E_{\text{bind}}}{10^{50} \text{ erg}} \right) \left( \frac{\chi}{0.1} \right)^{-1} M_\odot.$$  \hspace{1cm} (21)

During the NS merger with the core the Bondi-Hoyle accretion rate can get as high as $1 M_\odot \text{ s}^{-1}$ (Fryer & Woosley, 1998). In this regime neutrino-cooled accretion can take place as $\dot{M}_{\text{acc}} \gtrsim 10^{-3} M_\odot \text{ yr}^{-1}$ (Chevalier, 1993), and the accretion rate can get near the Bondi-Hoyle rate. Simulations by Ricker & Taam (2012) show that the actual rate can be much lower than the Bondi-Hoyle rate. In addition, Chevalier (1996) argued that angular momentum considerations can prevent neutrino cooling from occurring.

Here we take a different approach, we assume that jets are lunched during the merger with the core. These jets will move relative to the core material as the NS spirals-in and will deposit part of their energy inside the core. This will limit the accretion rate by a feedback mechanism; higher accretion rate will deposit more energy to the core and will suppress the accretion process.

The NS spirals inside the core within $\sim 5 - 10$ orbits, summing up to a total interaction time of $t_j \sim 1$ hour. The interaction of the jets with the core will take place within a radius of $R_i \sim 0.1 R_\odot$. This accretion rate is well below the Bondi-Hoyle rate and is comparable with the results of Ricker & Taam (2012). The result of the process will be probably observed as a type IIn SN (Chevalier, 2012).

Finally, when the NS is well inside the core, such that the core mass that is left is $\sim M_{\text{NS}}$, the rest of the core will form an accretion disk around the NS. This $\sim 1 M_\odot$ accretion disk will launch jets that will interact with gas at larger distances, $\sim 1 R_\odot$. This distance comes from the distance the mass expelled from the core at the escape speed of $\sim 1000 \text{ km s}^{-1}$ reaches within a fraction of an hour. Gamma Ray burst (GRBs) are observed to occur in Type Ic SN (Woosley & Bloom, 2006) and hence we don’t claim this system will be a GRB, as probably the jets will not penetrate the entire envelope.

3. IMPLICATIONS

If our claim that jets from NS can indeed remove the envelope and part of the core of RSG stars holds, we can think of two implications. Both of which require further study.
3.1. The red supergiant star HV2112

Levesque et al. (2014) attribute the peculiar abundances of some isotopes of the red supergiant (RSG) star HV2112 in the Small Magellanic Cloud to the star being a Thorne-Żytkow objects (TZO). However, some features, such as the high calcium abundance, are not accounted for by processes occurring in TZO. Tout et al. (2014) examined whether HV2112 can be a super asymptotic giant branch (SAGB) star, a star with an oxygen/neon core supported by electron degeneracy and undergoing thermal pulses with third dredge up. Tout et al. (2014) argue that a SAGB star can synthesis most of the elements that were used to claim HV2112 to be a TZO, e.g., molybdenum, rubidium, and lithium. But they find no way for a SAGB star to synthesis calcium. They still prefer the TZO interpretation for HV2112, and attribute the enriched calcium envelope to the formation process of the TZO. The calcium, they argue, can be synthesized when the degenerate electron core of a giant star is tidally disrupted by a neutron star and forms a disk around the NS, as in the calculations of Metzger (2012) for a WD merging with a NS. The high temperatures in such an accretion disk leads to calcium production. Interestingly, they find that the kinetic energy of the outflow from the accretion disk that is required to spread calcium in the giant, has enough energy to unbind the envelope. They postulate that the outflow is collimated, hence most of it escape from the star. We found in section 2 that the jets from the NS are formed while it is still in a Keplerian orbit, hence the jets are not well collimated, and the envelope and a large part of the core will be ejected.

The peculiar abundances of some isotopes might be related to the presence of a binary companion, e.g. lithium. The post AGB star HD172481, with a metallicity of [Fe/H] = −0.55, is in a binary system and has a very high lithium abundance Reynolds & Van Winckel (2001). Tout et al. (2014) also noted that RSG star can synthesis all elements, beside calcium. They argue against an enrichment by a supernova as the fraction of the ejecta that will be intercepted by HV2112 while still on the main sequence will be small.

Based on our calculations in section 2 we argue that TZO cannot be formed in the process where a NS spirals inside a RSG star. The jets launched by the accreting NS will expel the entire envelope. We instead propose that HV2112 had a companion just slightly more massive than HV2112 when both were on the main sequence. In such massive binary systems the lighter star expand to become a giant before the more massive star explodes (Sabach & Soker 2014). The probability of such an evolution is even more likely if the initially more massive star transfers mass to the less massive star via a Roche lobe overflow. The CCSN could have been a type Ib SN. At explosion, the radius of HV2112, $R_2$, could have been a sizable fraction of the orbital separation, $a$. It intercepted a fraction of $f \simeq 0.04(R_2/0.4a)^2$ of the SN ejecta. This ratio we use to replace equation (4) in Tout et al. (2014) where the factor is scaled to $f \simeq 4 \times 10^{-4}$. If, for example, the companion initial mass was $\sim 12M_\odot$, it could have ejected $\sim 0.01M_\odot$ of calcium
As the mass of calcium in HV2112 is estimated by Tout et al. (2014) to be $\sim 10^{-4}M_\odot$, it required that about a quarter of the SN ejecta that hit HV2112 during the explosion stays bound to it, for such an orbital separation. After the explosion the NS was kicked out of the binary system.

### 3.2. The r-process

Our analysis in section 2 points to three types of interaction of the NS jets inside the common envelope, CE-SN jets, with the star that could in principle take place. (i) Small amount of jet mass will interact with the low density envelope during the final stages of the inspiral inside the envelope. (ii) Then a jets’ mass of $\sim 0.01M_\odot$ will interact with the dense core when the NS enters the core. Interaction occurs within a distance of $\sim 0.1R_\odot$. The amount of mass carry by the jets and their typical distance of interaction with stellar mater in the above two types of jets is determined by the assumptions of the jet-feedback mechanism, and one has to bear in mind the large uncertainties. (iii) Finally, the central leftover of the core is destructed by the NS gravity and an accretion disk of $\sim 1M_\odot$ is formed around the NS. This disk is expected to launch jets with a total mass of $\sim 0.1M_\odot$, that catch-up with previously ejected core material at $\sim 1R_\odot$. The last two stages occur within few minutes, and the last launching episode, the most massive one, lasts for tens to hundreds of seconds.

R-process can generally occur both in the jets (Cameron 2001; Winteler et al. 2012) and in the post shock jets’ material (Papish & Soker 2012). In the type (i) jet interaction listed above the amount of jets material is small and their contribution to the r-process can be neglected. For the latter phases the post shock temperature can be estimated from the post shock radiation dominant pressure, $P = \frac{6 M_j \nu_j}{4 \pi \delta r^2}$

$$T \simeq 2 \times 10^8 \left(\frac{M_j}{10^{-4}M_\odot/\text{s}}\right)^{1/4} \left(\frac{\nu_j}{10^5 \text{km s}^{-1}}\right)^{1/4} \left(\frac{r}{R_\odot}\right)^{-1/2} \times \left(\frac{\delta}{0.1}\right)^{-1/4} \text{K.}$$

(22)

Here $\delta$ is the solid opening angle of the jet and $r$ is the radius where the jet is shocked. This is much too low for r-process to occur in the post shock jets’ material at a distance of $r \sim 0.1 - 1R_\odot$. In these cases r-process will occur inside the jets.

The flow structure studied here is different in key ingredients from two other types of jet launching models in CCSNe. In the jittering jets model (Papish & Soker 2014), listed in the second column of Table 1, jets are launched by a newly formed NS. However, each launching episode lasts for a short time, $< 0.1$ s, and the disk formed at each launching episode is short leaved. It is not clear that the fraction of neutron in the ejecta will be as high as in the case studied here where the
magnetic fields lift material from very close to the NS (Winteler et al. 2012). Another difference is that the high neutrino luminosity from the newly formed NS in the jittering jets model is likely to bring the ejecta closer to equilibrium, e.g., lower the neutron fraction. A third difference is the the jittering jets are expected to explode the star, and so they are shock relatively closed to the center $\sim 0.001 - 0.01 R_\odot$ (Papish & Soker 2012). Even if strong-r process elements have been synthesis in the jets, they will be disintegrated in the shock. In the flow studied in the present paper the shock is expected to take place much further out, and the core of the primary star has been already destroyed and formed the massive accretion disk now circling the NS.

Our flow structure is markedly different from the jets launched in GRB that are formed around black holes (BH). In the flow studied by Surman et al. (2006), for example, the jets are launched at $r = 100$ and 250 km from the center, compared with $\sim 15$ km in the present study, and the entropy considered is $s/k = 10 - 50$, higher than in the study of Winteler et al. (2012). The same holds for the neutrino wind in the study of Pruet et al. (2005), that within a very short time reaches an entropy per baryon of $s/k = 50 - 80$. In both Surman et al. (2006) and Pruet et al. (2005) the outflow starts as neutron-rich, $Y_e \sim 0.2$, but the high entropy implies that positron convert neutrons to protons.

In CCNSe the high neutrino luminosity of $L_\nu \sim 5 \times 10^{52}$ erg s$^{-1}$ can suppress the r-process by raising the electron fraction (reducing neutron fraction) through weak interactions (e.g., Pruet et al. 2006, Fischer et al. 2010). This has a large effect on the formation of r-process elements in neutrino driven winds and could affect to some degree the r-process in CCNSe jets (Winteler et al. 2012). In particular, high neutrino luminosity can suppresses the third peak of the r-process. The synthesis of the third peak, the strong r-process, is a rare process relative to the synthesis process of the first two peaks, as evident from the large abundance variations of Eu/Fe found in old stars (Cowan et al. 2011). Winteler et al. (2012) find that in their magnetic-jet simulation of the strong r-process a mass of $\sim 6 \times 10^{-3} M_\odot$ is synthesized. To account for the third peak abundance they require that one in $\sim 100$ CCSNe has the strong r-process.

Fryer et al. (2006) studied the ejection of matter from a supernova fallback as a site for the r-process. They found that the conditions in the ejecta are compatible with the production of the ’strong’ r-process for accretion rate similar to those in our proposed scenario, $\sim 3 \times 10^{-4} M_\odot$ s$^{-1}$ and have an initial electron fraction of $Y_e = 0.5$. In their calculations the ejecta is driven by energy released during the accretion onto the surface of the NS, but not in a jet like driven outflow.

The CE-NS jets could have the required properties to account for the strong r-process. First, based on Podsiadlowski et al. (1993), Chevalier (2012) estimated that $\sim 1\%$ of observed CCSNe are from a NS-core merger. The ejected mass in the jets in our proposed CE-NS scenario is $0.01 - 0.1 M_\odot$, which can lead to $\sim 0.001 - 0.01 M_\odot$ nucleosynthesis. This ratio is based on the simulations of jets in CCSNe performed by Nishimura et al. (2006) who found that the total
Table 1: Summary of the differences between CCNS jets, CE-NS jets and GRBs jets that provide possible sites for r-process nucleosynthesis. The properties of the jets in CCSNe are based on the jittering-jets model (JJM; Papish & Soker 2011), or the magnetic-jets studied by Winteler et al. (2012). The relative to all CCSNe number of CE-NS mergers is taken from Chevalier (2012). Data for GRBs is taken from Popham et al. (1999); Pruet et al. (2005). Only in the CCSN MHD jets and the NS-CE jets flow structures the accretion disk is both steady and bounded from inside by the NS surface. These lead to low entropy neutron-rich outflow that facilitate the nucleosynthesis of strong r-process (third peak) elements.

The amount of r-process elements is \( \sim 10\% \) of the total jets ejected mass. This mass is similar to what Winteler et al. (2012) have found.
4. SUMMARY

We studied the common-envelope (CE) evolution of a NS inside a red supergiant (section 2), and found that the NS is very likely to launch energetic jets that expel the entire envelope and most of the core. Hence, no Thorne-˙Zytkow objects (TZO) can be formed via the CE channel. We then discuss the implications of our results to the recent claim that the red supergiant (RSG) star HV2112 is a TZO ([Levesque et al. 2014; Tout et al. 2014]), and to r-process nucleosynthesis inside the jets.

In section 3.1 we proposed an alternative, an rare, scenario for the peculiar abundances of HV2112. Beside calcium, RSG can synthesis all elements with high abundances ([Tout et al. 2014]). We suggest that HV2112 had a companion slightly more massive than the initial mass of HV2112. The companion evolved first, but it exploded when HV2112 was already a giant ([Sabach & Soker 2014]). This implies that HV2112 intercepted a large fraction of the supernova ejecta, including a sufficient mass of calcium.

In section 3.2 discussed the possibility that jets launched by the NS as it mergers with the giant’s core could be a rare site for the strong r-process. Although most ingredients of the proposed scenario were studied in the past, they were never put together to yield the scenario we propose in this study. For example, the NS-core merger was studied in the past as a possible candidate for supernovae events where strong interaction with a dense environment takes place ([Chevalier 2012]). As the NS accretes mass from the giant at a very high rate due to neutrino cooling, an accretion disk is formed around the NS and two opposite jets are launched during the spiral-in process. We estimated the total energy deposited by the jets inside the envelope (eq. 15) using the jet-feedback mechanism ([Soker et al. 2013]), where energy deposit by the jets regulates the accretion rate. A small amount of accreted mass is sufficient to launch jets that expel the envelope (section 2.2).

In many cases the NS will merge with the core. We termed the jets launched by the NS during its interaction with the core ‘CE-NS jets’. In these cases we have found that much stronger jets are launched (section 2.3) to unbind and expel the outer parts of the core. The total mass launched by the jets in the outer part of the core is $\sim 0.01M_\odot$. The jets in this phase will interact with the surrounding core matter at a distance of $\sim 0.1R_\odot$. This is a too large distance for r-process to occur inside the post shock jets’ material due to low post-shock temperature (equation 22). However, r-process can take place inside the jets close to the center before they are shocked, much as in the MHD jets studied by [Winteler et al. 2012].

In the third and final phase when the NS is well inside the core an accretion disk with a mass of $\sim 1M_\odot$ is form around the NS from the destructed core. This accretion disk launches two opposite jets with a total mass of $\sim 0.1M_\odot$. We find that in total $0.01 - 0.1M_\odot$ of jets’ material is ejected by the NS as it interacts with the core (see Table I). Nucleosynthesis of r-process elements
can take place inside these jets (Cameron 2001) with a total r-process material that can be as high as \( \sim 0.01 M_\odot \).

We compared the properties of the CE-SN jets with jets launched in CCSNe and found that the flow studied here is similar to that of MHD jets launched by newly formed NS when the pre-collapse core is rapidly rotating (Winteler et al. 2012). Winteler et al. (2012) showed that under these conditions of low-entropy neutron-rich outflow the third r-process peak elements can be synthesis (the strong r-process). Lower neutrino luminosity of the NS in the NS-core merger (Table 1) favors the production of strong r-process in the CE-NS jets compare with CCSNe jets. The rareness of this process of \( \sim 1\% \) of the CCSNe rate (Chevalier 2012) can explain the large scattering of r-process elements in the early chemical evolution of the galaxy (Argast et al. 2004; Winteler et al. 2012).

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