Low energy core collapse supernovae in the frame of the jittering jets explosion mechanism

Roni Anna Gofman

and Noam Soker

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Department of Physics, Technion, Haifa, 3200003, Israel; rongof@campus.technion.ac.il; soker@physics.technion.ac.il

2

Guangdong Technion Israel Institute of Technology, Shantou 515069, Guangdong Province, China

ABSTRACT

We relate the pre-explosion binding energy of the ejecta of core-collapse supernovae (CCSNe) of stars with masses in the lower range of CCSNe and the location of the convection zones in the pre-collapse core of these stars, to explosion properties in the frame of the jittering jets explosion mechanism. Our main conclusion is that in the frame of the jittering jets explosion mechanism the remnant of a pulsar in these low energy CCSNe has some significance, in that the launching of jets by the newly born neutron star (NS) spins-up the NS and create a pulsar. We crudely estimated the period of the pulsars to be tens of milliseconds in these cases. The convective zones seed perturbations that lead to accretion of stochastic angular momentum that in turn is assumed to launch jittering jets in this explosion mechanism. We calculate the binding energy and the location of the convective zones with the stellar evolution code mesa. For the lowest stellar masses, we study, $M_{\text{ZAMS}} \approx 8.5 - 11 M_\odot$, the binding energy above the convective zones is low, and so is the expected explosion energy in the jittering jets explosion mechanism that works in a negative feedback cycle. The expected mass of the NS remnant is $M_{\text{NS}} \approx 1.25 M_\odot - 1.6 M_\odot$, even for these low energy CCSNe.

Keywords: Supernovae — stars: jets — pulsars: general

1. INTRODUCTION

In core-collapse supernovae (CCSNe) part of the core, or all of it and even part of the envelope, collapses to form a neutron star (NS), or a black hole, respectively. This process releases a huge amount of gravitational energy, most of which is carried by neutrinos, while a small fraction of the energy ejects the rest of the star.

There are two basic processes that, in principle, might deliver part of the gravitational energy of the collapsing core to the exploding gas, the ejecta. One process is heating of the in-flowing gas by neutrinos, where the most commonly studied is the delayed neutrino mechanism (Bethe & Wilson 1985). In the other process, jets that the newly born NS (or black hole) launches, even when the net angular momentum is very low, deliver the energy to the ejecta, this is the jittering jets explosion mechanism (e.g., Soker 2010; Gilkis & Soker 2014; Quataert et al. 2019). The jets operate in a negative feedback mechanism (Soker 2016b). Namely, when the jets manage to eject the outer parts of the core (or of the envelope in the case of black hole formation) accretions stops, and so are the jets.

Studies in recent years found that each of these two mechanisms requires one or more additional ingredients for a successful explosion. The problems of the delayed neutrino mechanism (e.g., Papish et al. 2015; Kushnir 2015) brought people who conduct CCSN simulations to introduce convection in the pre-collapse core (e.g., Couch & Ott 2013; Müller et al. 2019). These convective flow fluctuations lead to relatively large stochastic angular momentum variations of the flow onto the newly born NS. Some simulations show that these stochastic variations result in the formation of jittering jets, namely, the axis of a bipolar outflow changes its direction (Soker 2019b). The claim is that the extra ingredient that the delayed neutrino mechanism requires might be jittering jets (e.g., Soker 2019b).

The recent study by Sawada, & Maeda (2019) seems to support this claim. In most of the simulations that do reach an explosion, the process is slow, reaching the explosion energy in a time of $t_{\text{exp}} > 1$ s. Sawada, & Maeda (2019) argue that nucleosynthesis yields require explosion on a time scale of $t_{\text{exp}} \lesssim 0.25$ s, this brings them to “... suggest that there must be a key ingredient still missing in the ab-initio simulations, which should lead to the rapid explosion.” We take the view that this ingredient is the process of jittering jets.

Convective flow fluctuations in the pre-collapse core (in the case of NS formation) or envelope (in the case of black hole formation) are the base of the jittering jets explosion mechanism (Gilkis & Soker 2014,
2. THE RELEVANT PROPERTIES OF SUPERNOVA REMNANTS WITH PULSARS

There are several CCSNe with very low explosion energy of \( E_{\text{exp}} \approx 10^{49} - 10^{50} \) erg. These SN remnants (SNRs) contain a pulsar with a pulsar wind nebula (PWN; see, e.g., Martin (2014)). A famous case is the Crab Nebula with an explosion energy of \( E_{\text{exp}} \approx 10^{50} \) erg (e.g., Yang, & Chevalier 2015).

Reynolds, & Borkowski (2019) estimate the explosion energy of the G310.61.6 SNR that has a PWN to be very low, \( E_{\text{exp}} \approx 3 \times 10^{47} \) erg, and the ejected mass to be \( M_{\text{ej}} \approx 0.02 M_\odot \). This very low energy CCSN is a puzzle. Guest et al. (2019) estimate the kinetic energy, which is about the explosion energy, of the SNR G21.50.9 to be \( E_{\text{exp}} \approx 3 \times 10^{49} \) erg. Temim et al. (2019) study the SNR/PWN Kes 75 and conclude that the progenitor had a mass of \( M_{\text{ZAMS}} \approx 8 - 12 M_\odot \). They model this SNR with an explosion energy of \( E_{\text{exp}} \approx 6 \times 10^{50} \) erg. We note that some low energy CCSNe might be electron capture CCSNe (e.g., Nomoto et al. 2014). For that, we follow the oxygen core in the lower mass range of CCSNe.

The difference between the two explosion mechanisms concerning these CCSNe is that in the delayed neutrino explosion mechanism the presence of a pulsar, as opposed to a non-magnetic non-rotating NS, is of no significance, while in the jitting jets explosion mechanism the rotation and magnetic fields are the results of the launching of jitting jets by the newly born NS and the region around it.

The jitting jets explosion mechanism can account for the low explosion energy and relatively slow pulsar rotation at birth, i.e., much below break-velocity. van der Swaluw, & Wu (2001) find the typical spin period at birth to be \( \tau_s \approx 40 \) ms with a large scatter. The low explosion energy comes from the low binding energy of the ejecta. The accretion of gas with small amounts of angular momentum accounts for the slow rotation, while the large angular momentum fluctuations allow the launching of a jitting bipolar outflow (jitting jets; Soker 2019b and references therein).

Özel, & Freire (2016) review the masses of NS in binary systems, and find the mass distribution to be wide, \( 1 M_\odot \lesssim M_{\text{NS}} \lesssim 2 M_\odot \). Tang et al. (2019) use the NS equation of state to infer the masses of three isolated NSs. This method has much larger uncertainties than the methods for binary systems, and Tang et al. (2019) deduce a wide mass distribution for each one of the three. Crudely, the three NSs mass distribution is in the range of \( M_{\text{NS}} \approx 0.9 - 1.5 M_\odot \). The jitting jets explosion mechanism is sensitive to four parameters of the pre-collapse star: The angular momentum of the core (rotation velocity), the fluctuating convective flow in the core, the magnetic field in the core, and the binding energy of the ejected mass (Soker 2018, 2019a,b). These sensitivities explain the wide NS mass distribution. We do note that since the jitting jets explosion mechanism is sensitive to the angular momentum of the collapsing core, the outcome of an exploding star in a
close binary system might be different, in energy and explosion morphology, than that of a single star.

In what follows, we examine the binding energy and the location of the convective zones of the pre-collapse cores. We do not consider angular momentum and magnetic fields, and therefore our study is limited in its implications. Nonetheless, we can still shed light on the expected outcome of the jittering jets exploding mechanism of low mass stars.

3. NUMERICAL SET UP

We evolve single stellar models with ZAMS mass in the range of $8.5M_\odot - 15M_\odot$ and ZAMS metallicity of $Z = 0.02$ using the Modules of Experiments in Stellar Astrophysics code (MESA, version 10398 Paxton et al. 2011, 2013, 2015, 2018). We evolve the stellar models from pre-main sequence up to one of three evolutionary stages as follows: (1) $\text{Si}_{\text{nuc}}$ - oxygen is burning to create silicon, namely the total power from all nuclear reactions is high than $10^{49}L_\odot$; (2) $\text{Si}_{\text{core}}$ - a silicon core has formed and has mass larger than $1.5M_\odot$; or (3) $\text{Fe}_{\text{core}}$ - an iron core has formed and has began to collapse, namely the infall velocity is high than $1000$ km s$^{-1}$.

We use the MESA "Dutch" scheme for massive stars wind mass-loss. This scheme combines results from several paper and is based on Giebke et al. (2009) and is as follows. For stars with effective temperature, $T_{\text{eff}} > 10^4$ K and surface hydrogen abundance, $X_s$, above 0.4 we use Vink et al. (2001), and for such hot stars with $X_s < 0.4$ we use Nugis & Lamers (2000). In cases where $T_{\text{eff}} < 10^4$ K, we apply mass loss according to de Jager et al. (1988). We set the mass-loss scaling factor to be 0.8 since we assume that the stars do not rotate (Maeder, & Meynet 2001).

We employ mixing in convective regions defined by the Ledoux criterion according to a mixing-length theory (Henyey et al. 1965) with $\alpha_{\text{MLT}} = 1.5$ and $\alpha_{\text{sc}} = 1.0$ for semiconvection (Langer et al. 1983). We apply convective overshooting using a step function with an overshooting parameter of 0.335 (Brott et al. 2011).

4. STELLAR PROPERTIES

When presenting our results, we concentrate on properties that are relevant to the jittering jets explosion mechanism (section 1) concerning low-energy CCSNe with pulsar remnants (section 2). The two main properties are the pre-collapse binding energy of the mass ejected in the explosion and the perturbation due to convection in the pre-collapse core. Instabilities in the post-shock region above the NS amplify these perturbations (e.g., Kazeroni, & Abdikamalov 2020 for a recent paper), including large-amplitude variations in angular momentum of the gas accreted onto the NS (section 1).

The binding energy is relevant to the explosion energy because the jittering jets explosion mechanism operates in negative feedback, this implies that the explosion energy is about the binding energy for a high-efficiency explosion, and several times the binding energy for low efficiency (section 1).

We calculate the binding energy of the outer part of the core and the entire envelope, from a mass coordinate $M_{\text{in}}$ in the core to the stellar surface. The binding energy $E_{\text{bind}}$ includes the internal energy of the gas and the gravitational energy, and MESA supplied it.

In Fig. 1 we present binding energies for different initial masses and for models at the three evolutionary stages as follows (see section 3). (1) $\text{Si}_{\text{nuc}}$: Oxygen burning after production of some silicon. (2) $\text{Si}_{\text{core}}$: Just before the silicon starts to burn and there is a massive silicon core. (3) $\text{Fe}_{\text{core}}$: Just before collapse when there is a large iron core. Due to numerical problems, we could not run some low mass models to the phase of silicon burning.

We learn from the upper panel of Fig. 1 that for the mass coordinate $M_{\text{in}} = 1.65M_\odot$ the binding energy for all three stages is approximately similar for stars with $M_{\text{ZAMS}} > 10.5M_\odot$, namely, the binding energy above this mass coordinate does not change much during the formation of a silicon core and then an iron core. We extended this conclusion to include stars with $M_{\text{ZAMS}} < 10.5M_\odot$, and assume that their binding energy above $M_{\text{in}} = 1.65M_\odot$ at core-collapse is similar to that at $\text{Si}_{\text{nuc}}$ stage. We can assume the same, but with more significant differences between binding energies at the three different stages, for the mass coordinate $M_{\text{in}} = 1.55M_\odot$. We comment below on those that will explode as electron capture supernovae and will not reach a silicon core.

We note that for stars with $M_{\text{ZAMS}} \lesssim 10M_\odot$ electron capture before full oxygen burning might trigger core-collapse (e.g., Leung, & Nomoto 2019). In these cases, the binding energy at the stage $\text{Si}_{\text{nuc}}$ is a good approximation to the relevant binding energy at the explosion.

Taking these assumptions into account, stars with $M_{\text{ZAMS}} \lesssim 11M_\odot$ have rather low binding energies, $6 \times 10^{48}$ erg $\lesssim E_{\text{bind}} \lesssim 10^{50}$ erg above the mass coordinates $M_{\text{in}} = 1.65M_\odot$, and $10^{49}$ erg $\lesssim E_{\text{bind}} \lesssim 2 \times 10^{50}$ erg above the mass coordinates $M_{\text{in}} = 1.55M_\odot$. This is in line with earlier results, (e.g., Sukhbold et al. 2016) that for $M_{\text{ZAMS}} \lesssim 10M_\odot$ the core is less dense, and hence binding energy decreases with decreasing $M_{\text{ZAMS}}$.

Fig. 2 shows the convection velocity for the models we presented in Fig. 1 at the sage of $\text{Si}_{\text{nuc}}$ for models with
Figure 1. The binding energy integrated from 4 different mass coordinate $M$ in to $M^{\ast}$ as a function of the ZAMS mass. Models marked with magenta squares evolved up to oxygen burning ($\text{Si}_{\text{nuc}}$), models marked with blue diamond evolved up to silicon core formation ($\text{Si}_{\text{core}}$), and models marked with red triangles evolved up to iron core formation ($\text{Fe}_{\text{core}}$).

5. IMPLICATIONS

Although most of the findings we present in section 4 are not new by themselves, the way we present them, namely, binding energy and convective velocities, allows us to relate these properties to the formation of low energy CCSNe with pulsars to the jittering jets explosion mechanism. Namely, to relate the binding energy and location of convective velocities to the properties of the explosion and of the NS remnant. These properties are the explosion energy, NS mass, and NS spin period.

5.1. Explosion Energy and NS Mass

In the jittering jets explosion mechanism the accretion of gas with stochastic angular momentum onto the newly born NS is crucial. The stochastic angular momentum starts with convective fluctuations in the core (section 1), namely the convective velocities as we present in Fig. 2. For low mass stars that explode by electron capture the convective velocity is lower, but occurs at larger distances from the center (Fig. 3). The assumption is that the stochastic accretion of angular momentum lead to the launching of jets with the aid of neutrino heating (section 1). When the jets manage to eject the core, accretion stops (a negative feedback). As more mass is accreted, the energy of the jets increases, and the binding energy of the remaining mass decreases, as we see in Fig. 1.

From Fig 2 we learn that the convective regions occur at mass coordinate of $m \simeq 1.35 - 1.7 M_{\odot}$. These will seed fluctuations above the newly born NS that will lead to jittering jets. Such a baryonic mass forms a NS of mass $M_{\text{NS}} \simeq m - 0.1 M_{\odot} \simeq 1.25 - 1.6 M_{\odot}$ (Sukhbold et al. 2016). The explosion energy is the energy that the jets carry minus the binding energy. If we assume no fine tuning, we expect the explosion energy to be $E_{\text{exp}} \approx \text{few} \times 0.1 E_{\text{bind}} - \text{few} \times E_{\text{bind}}$.

From Figs. 1 and 2 the explosion energy of most stars with mass in the range of $8 \lesssim M_{\text{ZAMS}} \lesssim 10 M_{\odot}$, in the jittering jets explosion mechanism to be in the range of $E_{\text{exp}} \approx \text{several} \times 10^{48} \text{ erg} - 10^{50} \text{ erg}$. For most stars in the range $10 \lesssim M_{\text{ZAMS}} \lesssim 12 M_{\odot}$ we expect the jittering jets explosion energy to be $E_{\text{exp}} \approx 10^{50} - 10^{51} \text{ erg}$. In some cases the efficiency might be low, and explosion energy large, even much larger than the binding energy. This might be the case when the pre-collapse core is rapidly rotating and the jets are well collimated and break out along the fixed polar directions (Gilkis et al. 2016).

5.2. NS Spin Period
Figure 2. The convection velocity in km s\(^{-1}\) as a function of the mass coordinate at the age of Si\(_{\text{nuc}}\) for models with \(M_{\text{ZAMS}} < 10.5M_\odot\) (red mass label) and at the Fe\(_{\text{core}}\) stage for models with \(M_{\text{ZAMS}} \geq 10.5M_\odot\) (black mass label). The 4 vertical lines are the 4 mass coordinates, \(M_i\), for which we calculated envelope binding energy in Fig. 1: 1.35\(M_\odot\) in blue triangles, 1.45\(M_\odot\) in orange diamonds, 1.55\(M_\odot\) in yellow squares, and 1.65\(M_\odot\) in purple circles.

We can crudely estimate the angular momentum that the jets carry. An opposite amount is ‘left’ in the newly born NS (pulsar).

We make the following assumptions and definitions.
(1) We assume that the jets remove the ejecta with an efficiency \(\eta_{\text{eff}} \equiv E_{\text{bind}}/E_{\text{jets}} < 1\), so that the explosion energy is

\[
E_{\text{exp}} = E_{\text{jets}} - E_{\text{bind}} = E_{\text{jets}} (1 - \eta_{\text{eff}}),
\]

where \(E_{\text{jets}}\) is the jets energy, and \(\eta_{\text{eff}} \approx 0.5\). (2) We assume the jets have a terminal specific energy, mostly kinetic energy, about equal to the specific escape energy from their average launching radius \(r_{\text{jets}}\). This gives a terminal velocity of about the escape speed, \(v_{\text{jets}} \approx v_{\text{esc}} = \sqrt{2GM_\odot/r_{\text{jets}}}\), such that the mass carried by the jets is

\[
M_{\text{jets}} = \frac{2E_{\text{jets}}}{v_{\text{jets}}^2} = \frac{E_{\text{exp}}r_{\text{jets}^3}}{GM_\odot} (1 - \eta_{\text{eff}})^{-1}. \tag{2}
\]

(3) We assume that the specific angular momentum of the jet is that at its average launching radius \(j_{\text{jets}} = (GM_\odot r_{\text{jets}})^{1/2}\). (4) We take \(N\) stochastic jet-launching episodes.

Substituting for the jet velocity we can write the total angular momentum that the jets carry as

\[
J_{\text{jets}} = \frac{M_{\text{jets}}j_{\text{jets}}}{\sqrt{N}} = \frac{E_{\text{exp}}}{\sqrt{N}} \frac{r_{\text{jets}}^{3/2}}{GM_\odot} (1 - \eta_{\text{eff}})^{-1}. \tag{3}
\]

If it is only due to this angular momentum that the NS spins, i.e., the pre-collapse core has zero angular momentum, then the spin period of the newly born NS is
Figure 3. The convective velocity in \( \text{km s}^{-1} \) as a function of the radius in a logarithmic scale at the Si\(_{\text{nuc}}\) stage for the M\(_{\text{ZAMS}}\) < 9.5\( M_\odot \) model, and at the Fe\(_{\text{core}}\) stage for the two lower models. The 4 vertical lines have the same meaning as in Fig. 2.

\[ \tau_s = 2\pi I_{\text{NS}} / J_{\text{jets}}. \]

This reads

\[
\tau_s \approx 64 \left( \frac{1 - \eta_{\text{eff}}}{0.5} \right) \left( \frac{\sqrt{N}}{\sqrt{10}} \right) \left( \frac{E_{\text{exp}}}{10^{50} \text{ erg}} \right)^{-1} \\
\times \left( \frac{M_{\text{NS}}}{1.4M_\odot} \right)^{1/2} \left( \frac{r_{\text{jets}}}{100 \text{ km}} \right)^{-3/2} \left( \frac{I_{\text{NS}}}{1.5 \times 10^{45} \text{ g cm}^2} \right) \text{ ms},
\]

where we take the moment of inertia of the NS, \( I_{\text{NS}} \), from Worley et al. (2008).

Equation (4) has several implications. We here mention two. The first implication is for the most energetic explosions, namely, CCSNe with explosion energies of \( E_{\text{exp}} \gtrsim 10^{52} \text{ erg} \). In these cases, the spin period according to the jittering jets explosion mechanism reaches the shortest possible value of \( \tau_s \approx 1 \text{ ms} \). If the NS magnetic field is strong enough, we have an energetic magnetar. Namely, energetic magnetars come along with energetic jets in the explosion (Soker 2016a; Soker, & Gilkis 2017).

The other implication is relevant to our study of the least energetic CCSNe. For these CCSNe, the total angular momentum that the jets leave on the NS is very low, corresponding to \( \tau_s \approx \text{few} \times 10 - 100 \text{ ms} \). These values are compatible with the observed values of \( \tau_s \approx 40 \text{ ms} \) (van der Swaluw, & Wu 2001), and with new expectation of slow NS birth rotation (Fuller et al. 2019).

6. SUMMARY

We calculated the binding energy of the outer core and envelope, and located the convection regions in the core, as both properties are related to the jittering jets explosion mechanism. We related (sec. 5) these to three observational properties of SNRs and their pulsar, i.e., the SN explosion energy, the pulsar mass, and the pulsar spin period. Using the numerical stellar evolution code MESA, we evolved stellar models with a mass in the range of 8.5\( M_\odot \) \( \leq M_{\text{ZAMS}} \leq 15\( M_\odot \), and we concentrated in the lower masses. We calculated the binding energy at three different evolution stages, during oxygen burning to silicon, after the formation of a massive silicon core, and just before core collapse when the inner part is iron. We presented the binding energies of mass residing above four mass coordinates in Fig. 1.

We found that most models feature convective zones somewhere between at the mass coordinate 1.35\( M_\odot \) and 1.7\( M_\odot \) (Fig. 2). For low mass stars in our calculations where the convection velocity is slow, the convection region is at a larger radius (Fig. 3), thus implying that the angular momentum fluctuations are of similar significance in all cases. The convective regions seed the perturbations that lead to stochastic angular momentum accretion onto the newly born NS (or black hole), that are assumed to drive to the launching of jittering jets.

Though the calculations of binding energies and the locations of the convective zones are not new on their own, we have presented them together and associated them via the jittering jets explosion mechanism to the properties of the SNRs and their pulsar (Sec. 5). The jittering jets explosion mechanism works in a negative feedback cycle, such that when the jets manage to eject the core the accretion ceases, and so are the jets. This implies that the explosion energy is of an order of magnitude of the binding energy of the pre-collapse outer core and envelope, namely the mass ejected at the explosion. For the lowest mass stars we studied the binding energy can be very low. From Fig. 1 we conclude that the binding energy above the mass coordinates...
$M_{\text{in}} = 1.65M_\odot$ and $M_{\text{in}} = 1.55M_\odot$ does not change much during the formation of a silicon core and later or an iron core. Stars with $M_{\text{ZAMS}} \lesssim 11M_\odot$ have rather low binding energies of $6 \times 10^{48}$ erg $\lesssim E_{\text{bind}} \lesssim 10^{50}$ erg above the mass coordinates $M_{\text{in}} = 1.65M_\odot$, and $10^{49}$ erg $\lesssim E_{\text{bind}} \lesssim 2 \times 10^{50}$ erg above the mass coordinates $M_{\text{in}} = 1.55M_\odot$.

The presence of convective zones in the mass coordinate range above which binding energy is low for the lowest mass stars we have studied implies for the jittering jets explosion mechanism that the mass of the newly born NS is $M_{\text{NS}} \approx 1.25M_\odot - 1.6M_\odot$, even for low energy CCSNe.

Our main conclusion is that in the frame of the jittering jets explosion mechanism, the remnant of a pulsar has some significance. The jets carry with them angular momentum, and therefore the opposite amount of angular momentum is left to spin-up the NS and create a pulsar. We crudely estimated the period of the pulsars (Subsec. 5.2) to be tens of milliseconds (eq. 4).

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