JITTERING-JETS EXPLOSION TRIGGERED BY THE STANDING ACCRETION SHOCK INSTABILITY

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ABSTRACT

We show that the standing accretion shock instability (SASI) that has been used to ease the shock revival in core collapse supernovae (CCSNe) neutrino-driven explosion models, might play a much more decisive role in supplying the stochastic angular momentum required to trigger an explosion with jittering jets. We find that if the kinetic energy associated with the transverse (non radial) motion of the SASI is larger than about ten percent of the energy associated with the energy of the accreted gas, then the stochastic angular momentum can reach about five percent of the Keplerian specific angular momentum around the newly born neutron star. Such an accretion flow leaves an open conical region along the poles with an average opening angle of about 5 degrees. The outflow from the open polar regions powers an explosion according to the jittering-jets model.

Key words: stars: massive — supernovae: general

1. INTRODUCTION

Core-collapse supernovae (CCSNe) are explosions of massive stars. A huge amount of gravitational energy, more than $10^{51}$ erg, is released by the newly formed neutron star (NS), or black hole (BH). The manner by which a small fraction of this energy is channeled to explode the star is an open question. The two contesting processes for explaining all CCSNe are the delayed neutrino mechanism (e.g., Wilson 1985, Bethe & Wilson 1985 and Janka 2012 for a review) and the jittering-jets mechanism (Papish & Soker 2011, 2012, 2014; Gilkis & Soker 2014). Explosions based on jets formed in cases with pre-collapse rapidly rotating cores exist as well (e.g. LeBlanc & Wilson 1970, Khokhlov et al. 1999, Lazzati et al. 2012), but these models can account for a limited number of rare types of CCSNe.

Another recent revisited model is the collapse-induced mononuclear explosion (CITE) model (Burbidge et al. 1957, Kushnir & Katz 2014). In this model a helium-oxygen shell that is compressed during the collapse is detonated and then unbinds the outer stellar layers. The CITE model can result in up to a few $10^{51}$ erg of kinetic energy under very tuned parameters (Kushnir 2015).

The delayed-neutrino mechanism faces two challenges. The first one is to revive the stalled shock of the inflowing core gas, and the second challenge is to achieve the desired $\gtrsim 10^{51}$ erg = 1 foe observed explosion kinetic energy. We note that highly energetic explosions (e.g., ASASSN-15lh, Dong et al. 2015) cannot be explained by the neutrino mechanism while it can be accounted for with the jittering-jets model that is based on a negative feedback mechanism (Gilkis et al. 2015). The incapability of the delayed-neutrino mechanism to overcome these two obstacles in a consistent and persistent manner is mirrored in the varying, and sometimes conflicting, outcomes of increasingly sophisticated multidimensional core collapse simulations (e.g., Bethe & Wilson 1985, Burrows & Lattimer 1985, Burrows et al. 1995, Fryer & Warren 2002, Buras et al. 2003, Ott et al. 2008, Marek & Janka 2009, Nordhaus et al. 2010, Brandt et al. 2011, Hanke et al. 2012, Kuroda et al. 2012, Hanke et al. 2012, Mueller et al. 2012, Brüenn et al. 2013, Mueller & Janka 2014, Mezzacappa et al. 2014, 2015). For some other difficulties of the delayed neutrino mechanism see Kushnir (2015).

To ease the revival of the stalled shock in neutrino-based explosion models, dynamical effects, like pre-collapse convection and/or rotation, have been studied in great details in recent years. Couch & Ott (2013), Couch & Ott (2015), and Mueller & Janka (2015) introduced pre-explosion turbulence in the core. They found that after collapse the turbulence is carried to the post-shock region, and an effective turbulent ram pressure exerted on the stalled shock allows shock revival with less neutrino heating. Abdikamalov et al. (2014), however, find that increasing the numerical resolution allows a cascade of turbulent energy to smaller scales, and the shock revival becomes harder to achieve.

The main challenge of the jittering-jets model, on the other hand, is to supply a large enough specific angular momentum to the mass accreted onto the NS to form an accretion disk or an accretion belt. A belt is defined as a thick sub-Keplerian accretion disk that does not extend much beyond the NS, but has sufficiently large specific angular momentum to prevent an inflow along the two opposite polar directions. Gilkis & Soker (2013) showed that the above assumed pre-collapse turbulence lead to the formation of intermittent thick accretion disks, or accretion belts, around the newly born NS. The implication of their results is that the pre-collapse turbulence assumed by Couch & Ott (2013), Couch & Ott (2015), and Mueller & Janka (2015) facilitated much more the jittering-jets model than the delayed neutrino mechanism.

Another dynamical effect that has been studied in relation to the delayed neutrino mechanism is the standing accretion shock instability (SASI) that develops in the post-shock inflowing core material (Blondin et al. 2003, Blondin & Mezzacappa 2007, Fernández 2010, Burrows et al. 1995, Janka & Mueller 1998, Buras et al. 2006, Ott et al. 2008, Marek & Janka 2009). Most interesting to our present study is the spiral modes of the SASI that includes transverse motion that carries local angular momentum variations. The local variations can add up to non-zero angular momentum. Rantsiou et al. (2011), for example, suggested the spiral modes of the SASI as the source of pulsar angular momentum. It was found that the spiral modes of the SASI can reduce the neutrino flux that is...
required to revive the stalled shock, e.g., Fernández (2015) and earlier references therein. We note that even if the stalled shock is revived, the delayed neutrino mechanism encounters a severe obstacle in achieving 1 foe (Papish et al. 2013).

In the present paper we study the implications of the results of Fernández (2015) on the jittering-jets model. As we show, the SASI might play a significant role in facilitating the jittering-jets model, hence might solve the biggest challenge of the jittering-jets model. In section 2 we describe the way the opening angle along the two opposite polar directions is calculated. In section 3 we calculate this angle from the results presented by Fernández (2010). Our short summary is in section 4.

2. ACCRETION BELT

We consider a scenario where material falling on the proto-NS has a temporary angular momentum in some direction, which we denote as the positive z-axis. As the material possesses a specific angular momentum \( j \neq 0 \), the accretion will be limited to some angle \( \theta_a \) from the z-axis. This angle, \( \theta_a \), can be estimated from the magnitude of the angular momentum by the balance between the centrifugal and gravitational forces. At a point on the NS surface and at an angle \( \theta \) from the z-axis, the centrifugal force is \( F_c = \frac{j^2}{(R_{NS} \sin \theta)^3} \) and the opposing gravitational component is \( F_G = GM_{NS} \sin \theta / R_{NS}^2 \), where \( M_{NS} \) and \( R_{NS} \) are the proto-NS mass and radius, respectively. The required specific angular momentum for limiting the accretion to an angle \( \theta_a \), is obtained by equating the two forces

\[
j_z = \sqrt{GM_{NS}R_{NS} \sin^2 \theta_a}, \tag{1}
\]

and the limiting angle is

\[
\theta_a = \sin^{-1} \sqrt{\frac{j_z}{J_{Kep}}}, \tag{2}
\]

where \( J_{Kep} = \sqrt{GM_{NS}R_{NS}} \).

It is important to emphasize that the open polar regions (or ‘avoidance regions’ as they are avoidance regions for the incoming gas), do not serve to collimate the outflow. Even for thin accretion disks where the opening angle is close to 90°, e.g., as in young stellar objects, there are jets. The role of the avoidance regions is to allow bipolar mass outflow as a result of the magnetic activity in the accretion belt (see below).

Furthermore, as the open polar regions do not have a specific role, there is no threshold on their value. The collimated outflow is formed by magnetic activity where there are two opposite preferred directions (the rotation axis) along which the pressure of the inflowing gas is very low. The magnetic activity then leads to an outflow along these directions (Schreier & Soker 2016). The situation is such that there is a monotonic relation between the low pressure of the incoming gas (which can be even zero) and the limiting angle. Numerical simulations are required to determine the value of the low pressure of the incoming gas that allows for an outflow to develop. Our estimate, that must be checked with 3D numerical simulations, is that for \( \theta_a \) larger than about 0.1 (several degrees) a bipolar outflow will develop.

This calculation of the limiting angle \( \theta_a \) is under the assumption of a uniform specific accreted angular momentum \( j = \langle j \rangle \). In most cases the specific angular momentum is not uniform. Material with lower angular momentum can flow through the poles with an angle \( \theta < \theta_a \), while material with higher angular momentum will form an accretion belt with a higher limiting angle \( \theta_a \) than what is assumed here. In general the limiting angle \( \theta_a \) in equation (2) represents some average behavior.

In Gilkis & Soker (2015) this approach was used to show that if before collapse there exist high convective velocities in the progenitor, such as those presented by Couch & Ott (2013, 2015) and Mueller & Janka (2015), those velocities can give rise to the required stochastic angular momentum needed for an accretion belt.

In this work we consider the stochastic angular momentum resulting from post-bounce dynamical SASI instabilities. The schematic flow structure discussed here, including stochastic angular momentum from the pre-collapse core and the SASI, is presented in Figure 1.

3. ACCRETION BELTS FROM THE SASI SPIRAL MODES

Fernández (2010) studied the spiral modes of the SASI using 3D simulations. He found that the SASI leads to a redistribution of the angular momentum accreted onto the proto-NS.

This angular momentum was less than the Keplerian angular momentum close to the proto-NS and no accretion disk was formed. In this section we revisit the results of Fernández (2010) and show that the SASI can lead to a belt-like structure around the proto-NS. We speculate that as a result of the belt-like flow, jets will be launched and explode the star (Schreier & Soker 2016).

The angular momentum accreted onto the proto-NS in the simulations conducted by Fernández (2010) can be estimated from the rate of change of the proto-NS rotational period \( T \), as presented in his figure 17 for five cases. The rate of change of the angular momentum near the proto-NS is

\[
\dot{j} = \dot{I} \omega = -I \frac{2\pi}{T^2} \dot{T}. \tag{3}
\]

For the mass inflow rate of \( \dot{M}_{acc} \approx 0.3M_{\odot} \, \text{s}^{-1} \) and a NS moment of inertia \( I = 10^{45} \, \text{g} \, \text{cm}^2 \) used in the simulations, we can estimate the specific angular momentum of the accreted mass as function of time,

\[
j = 1.75 \times 10^{15} \left( \frac{j}{7 \times 10^{45} \, \text{g} \, \text{cm}^2 \, \text{s}^{-1}} \right) \left( \frac{\dot{M}_{acc}}{0.3M_{\odot} \, \text{s}^{-1}} \right) \, \text{cm}^2 \, \text{s}^{-1} \tag{4}
\]

using the results of Fernández (2010).

The accreted specific angular momentum \( j \) calculated by equation (4) is presented in the left panels of Figure 2. The values of \( \dot{M}_{acc} \) and \( I \) are as scaled in equation (4), while \( T \) and \( \dot{T} \) are from Figure 17 of Fernández (2010). We also plot the limiting angle \( \theta_a \) calculated from equation (2), with the scaling of

\[
J_{Kep} = 2.16 \times 10^{16} \left( \frac{M}{1.4M_{\odot}} \right)^{1/2} \left( \frac{R}{25 \, \text{km}} \right)^{1/2} \, \text{cm}^2 \, \text{s}^{-1} \tag{5}
\]

for the same cases in the right panels of the same figure. As can be seen, the specific angular momentum is indeed lower.
by an order of magnitude than that required to form an accretion disk around the proto-NS. However, we find the limiting angle, $\theta_o$, to be large enough to create a belt like structure around the proto-NS in most cases.

Let us dwell on some of the ingredients of the proposed mechanism. In a recent paper (Möst et al. 2015) conducted very high resolution simulations of CCSNe with pre-collapse rapidly rotating cores. They showed that rapidly rotating material around the newly born NS can substantially amplify magnetic fields, with an e-folding time scale of $\tau_\phi \approx 0.5$ ms. In their simulations this is about half an orbital period in the region of the disk.

It is important to note the following properties of the results obtained by Möst et al. (2015). (1) Möst et al. (2015) obtained significant magnetic field amplification only for very high spatial resolution simulations.

(2) The amplification reaches saturation when the magnetic energy density is about equal to the turbulent energy density (equipartition). In their simulations this occurs within 3 ms. Had the initial magnetic field been weaker, amplification would have lasted longer, still reaching equipartition. (3)

![Diagram of proposed scenario](image)

**Fig. 1.** A schematic presentation of the proposed scenario. The panels are not exactly to scale, but the two-sided arrow on the upper left of each panel is approximately 500 km. The four panels span an evolution time of several seconds. (a) In the silicon burning shell of the pre-collapse core there is a convective region, at about thousands of km from the center. The convective vortices are a source of the stochastic angular momentum. (b) After collapse and the formation of a neutron star (NS) the rest of the infalling gas passes through the stalled shock. The stochastic spatial distribution of angular momentum in the silicon burning shell is carried inward into the post-shock region. In addition, the spiral modes of the SASI add stochastic angular momentum in the post-shock region. (c) The accreted angular momentum changes stochastically in magnitude and direction. For short periods of times, tens of milliseconds, the accreted gas near the NS possesses a net angular momentum. Accretion along and near the temporary poles of the NS changes the angular momentum in the silicon burning shell is carried inward into the post-shock region. (d) The accreted angular momentum changes stochastically in magnitude and direction. For long periods of times, tens of milliseconds, the accreted gas near the NS possesses a net angular momentum. Accretion along and near the temporary poles of the NS changes the angular momentum in the silicon burning shell is carried inward into the post-shock region.

The amplification time at a radius of about 40 km is about ten times as long as in the inner radius. This increase in amplification time results from two factors. Firstly, the Keplerian orbital period at 40 km is larger by a factor of about 4 relative to that at a radius of 15 km. Secondly, the shear is large near the NS. In the scenario proposed by (Schreier & Soker 2016) the amplification occurs near the surface of the NS, hence the amplification time of the magnetic field is expected to be short.

The Keplerian orbital period at ~ 25 km from the newly born NS is 1.8 ms. From Fig. 2, we see that a typical temporary disk last for about 5 – 10 ms, that is 3-6 times the orbital period. From the results of Mösta et al. (2015) the magnetic fields can be amplified by $\approx \exp(5 - 12) = 100 - 10^3$.

According to Schreier & Soker (2016) it is the amplification of the magnetic field that is the most important ingredient in the launching of jets from accretion belts. The second parameter in importance is the opening angle $\theta_o$. The reason for the higher importance of the magnetic fields is that the magnetic activity can change the opening angle in the following ways.

Schreier & Soker (2016) suggest that reconnection of the magnetic field lines eject gas through the two opposite polar avoidance regions. This activity can increase the opening angle in the inflowing gas. Schreier & Soker (2016) further argue that winding of the magnetic field lines frozen to the polar outflow can further channel rotation energy to outflow kinetic energy. Magnetic tension can further increase the opening angle. The main conclusion is that once the magnetic field becomes strong, the opening angle is opened to $\theta_o \geq 0.1 = 6^\circ$.

There is no upper limit on the value of $\theta_o$, as the scenario for jet launching from accretion belts does not require the belt to collimate the bipolar outflow.

4. SUMMARY

In recent years dynamical effects, like pre-collapse convection and/or rotation, have been introduced in simulations of neutrino-driven explosion of CCSNe. The hope was that these effects will help revive the stalled shock, and lead to the desired explosion energy that has not
consistently achieved with neutrino-based mechanisms. The dynamical effects include the SASI (e.g., Blondin et al. 2003; Blondin & Mezzacappa 2007; Fernández 2010) and pre-core-collapse perturbations and turbulence (e.g. Couch & Ott 2013, 2015; Mueller & Janka 2015). These dynamical effects have been shown to have only limited effects on helping a successful explosion by the delayed-neutrino mechanism. However, these effects might help in creating accretion belts and so might be important ingredients in the jittering-jets model for CCSNe.

In a former paper Gilkis & Soker (2015) studied the influence of pre-collapse core turbulence on the jittering-jets model, and found it to help with supplying the stochastic angular momentum. In this paper we study the influence of the SASI on the creation of intermittent accretion belts. The schematic flow structure is presented in Figure 1. To calculate the specific angular momentum of the accreted mass we use the study of the SASI spiral modes conducted by Fernández (2010). We found that during many time intervals the average specific angular momentum of the accreted mass is \( \approx 5\% \) of the Keplerian angular momentum on the equator of the newly formed NS (left panels of Figure 2). This implies that a cone with an angle of \( \theta_a \approx 10^\circ \) from the temporary angular momentum axis will be almost devoid of accreted gas close to the NS. The temporal variations of the angle \( \theta_a \) according to four cases of the SASI studied by Fernández (2010), are given in the right panels of Figure 2. If magnetic fields are amplified in the accretion belt, due to sheared rotation and converging accretion flow, jets might be launched along the empty polar cones (Schreier & Soker 2016). This is a basic assumption of the jittering-jets model.

We note that the CITF thermonuclear explosion mechanism for CCSNe studied by Kushnir & Katz (2014) and Kushnir (2015a) requires a large amount of angular momentum in the core to achieve the desired explosion energy from the thermonuclear burning of the mixed helium-oxygen layer. The collapsing rapidly rotating core supplies a vast amount of mass to form an accretion disk around the newly formed NS; about \( 1M_\odot \) with a specific angular momentum of \( j \approx 4 \times 10^{17} \text{ cm}^2 \text{s}^{-1} \). The energy carried by the expected jets will dwarf the energy released by the thermonuclear burning (Gilkis et al. 2015).

Although the results of this paper and Gilkis & Soker (2015) are only preliminary, they show that it might be possible to achieve the conditions for jets launching in CCSNe. If this is correct then the jittering-jets model will be able to explode a star with the desired 1 foe explosion energy (Papish & Soker 2014b). There are many more points that should be addressed before we can claim more conclusively that the jittering-jets model can work. This include simulations of magnetic fields amplification in the accretion belt and further investigating the ability of it to launch jets.

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