A new explosion mechanism for core-collapse supernovae

Mario Everaldo de Souza
Physics Dept., Universidade Federal de Sergipe, 49,100-000 São Cristóvão, Sergipe, Brazil

Abstract

It is proposed that the explosion, or actually, the fast expansion of the envelope of a core-collapse supernova is caused by the action of a powerful electric field that is formed as a consequence of the action of the shock wave on the interface between the proto-neutron star and the plasma of the envelope during the first minutes of the collapse. The proposal explains also the shell-like shape of core-collapse supernovae remnants, the reason why there are different ejecta velocities and the origin of the radial magnetic field which has been observed in young supernovae and shows that a supernova is a very powerful particle accelerator. It is shown for the first time how the dynamics of the explosion is clearly connected to the light curve of the supernova. It is calculated that the radius of supernova KSN 2011d is about 411.4 solar radii.

Keywords: core-collapse supernovae – supernovae – KSN 2011d

1 INTRODUCTION

There has been great theoretical progress in the description of core-collapse supernova phenomena. The formation of the shock wave in these types of supernovae is very well understood and described as well as the formation of the neutron star in the core. There is a vast literature that describes the processes of formations of the neutron star and of the shock wave. As examples there are the excellent works by Foglizzo et al. (2015), Janka (2012) and Lisakov (2018).

As discussed by many authors what is not well understood is how the neutrinos generated in the star core during its collapse transfer enough energy to the star envelope to make it explode Janka (2012), Foglizzo et al. (2015). Some authors mention that there may be another mechanism that drives the explosion in the star envelope. For example, Janka (2012) says in the summary of his cited article "Spherically symmetric simulations, Newtonian and general relativistic, with the most advanced treatment of neutrino transport by solving the Boltzmann equation, do not produce explosions. This emphasizes the importance of convection, but may also point to physics still missing in the models." This article proposes an ingredient for the Physics that is missing.

It is worth recalling that when the shock wave hits the envelope plasma of the star a high pressure region and a low pressure region are created in front of the wave and behind it, respectively. Therefore, it is expected that some turbulence is immediately developed, but the important question is to evaluate if this turbulence explodes the star. The answer is no. This is clearly seen in the video https://www.youtube.com/watch?v=kLlILnQjGfc which shows the animation of the early flash of supernova KSN 20011d caught by the Kepler Space telescope. If the turbulence generated by the shock wave had been the cause of the explosion, then the explosion would have begun together with the shock wave, but this did not happen because the explosion, actually, a very fast expansion, began about 20 minutes later on and lasted a long time. This is in line with the smooth rise of the light curve of this supernova. If there had been too much turbulence the light curve would be full of big spikes. There are yet two very important facts against the big role of turbulence in supernova explosions: 1) over time there is the formation of a hollow region around the neutron star that becomes more visible in older remnants; if turbulence played a very important role this hollow region would not exist; 2) if turbulence played an important role in supernova explosion the remnants would not have any symmetry at all. It is well known that supernovae remnants have in general the shape of an oblate ellipsoid, almost spherical, although more ellipsoidal shapes exist such as the one of the Crab supernova.

I do not think that neutrinos can transfer a lot of energy to the plasma of the envelope because neutrinos almost do not interact with the plasmas of stars. This is a very well-known fact. Of course, neutrinos interact a lot with the very dense matter in the centers of stars where they take part in the fusion process, but once they are released from the star core they reach the star surface almost without having had any interaction at all. In the sun, for example, only the very energetic neutrinos interact with the plasma and let us have in mind that the sun's average density is at least about ten times larger than the average density in red giants plasmas. As Pejcha (2020) says in an important article on core-collapse supernovae "It is worth noting that the concept of neutrino mechanism assisted by instabilities is far from proven." What is then the cause of the explosion?

2 THE FORMATION OS ELECTRIC AND MAGNETIC FIELDS IN THE ENVELOPE OF THE PROGENITOR STAR DUE TO THE ACTION OF THE SHOCK WAVE

This model is based on the assumption that the main cause of a core-collapse supernova explosion is the formation of electric and magnetic fields in the progenitor star envelope by the shock wave. This idea has not yet been proposed by other researchers up to now because it has always been admitted that any macroscopic volume of the progenitor star plasma has always zero electric charge on average and also because it has been taken for granted that the shock wave is always collisionless all the way from the core of the star up to the star surface. But this is not the case at the interface between the proto-neutron star and the plasma immediately after the interaction of the shock wave with this interface. As shown by Bellei & Amendt (2017) "According to particle-in-cell and multi fluid simulations, as a shock propagates across an unperturbed classical interface significant amounts of rearward shocked material are predicted to advect with the shock front over distances that are much larger than a ion-ion collisional mean free path of a shocked ion. This novel mechanism for interface mixing is found to scale strongly with Mach number ($\sim M4$) and produces an ion population bunch that penetrates the upstream material at nearly the shock speed." On page 5 of the mentioned article the authors say "A total of 150 simulations are performed. The amount of mix at shock flash, measured as the mass of DT shellions between R=0 and R=80 µm at shock flash, over the initial mass of the gas, is shown as a two-dimensional map in Figure 6b. As the map demonstrates, the mix level increases substantially with background temperature and Mach number." To date in the case of supernova what has always been considered in the literature is that the shock wave is always collisionless even at interfaces between different layers of matter, but has to be wrong according to the findings of Bellei & Amendt (2017) due to the action of the shock wave between interfaces. Extending the findings of Bellei & Amendt (2017) to the case of a supernova, as a result of the interaction of the shock wave with the interface between the proto-neutron star and the plasma, ions will penetrate the envelope plasma at very high speeds. Let us have in mind that in the case of a supernova the shock wave has almost the velocity of light and that the temperature is extremely high so that the mixing is favored. The mixing is also favored because the shock wave comes from a denser medium at the interface and penetrates a less denser region in the envelope plasma. It is also important to consider that the whole process since the beginning of the generation of the shock wave up to its interaction with the interface above mentioned is too fast for any balancing between the proto-neutron star and the envelope plasma. Therefore the assumption that a bunch of protons from the proto-neutron star penetrate into the envelope plasma during the shock wave interaction with the interface is very reasonable. And moreover as we will see below only a very tiny fraction of protons and electrons take part in the formation of the electric and magnetic fields.

In this article I will consider always the case of type IIP supernova. For other types of core-collapse supernova we just need to change the positive ions as in the case of type Ib supernovae which have very rich helium envelopes. In the case of a type IIP supernova the progenitor star is a red giant with an envelope that is very rich in hydrogen, that is, the envelope plasma is mainly constituted of protons and electrons in equal parts, so that the total charge of the plasma is zero and any small macroscopic volume of the plasma has zero charge. This is true before the action of the shock wave. But as argued above the ions of the envelope, that is, protons and electrons close to the proto-neutron star surface, acquire high speeds but the speeds of electrons are much larger than those of protons because they are very light in relation to protons. Of course, there are many shocks between particles of different layers close to the proto-neutron star surface, but due to the very different masses between electrons and protons, protons lag behind electrons. Due to the lagging of protons with respect to electrons there is the buildup of a region inside the plasma, just above the proto-neutron star, with an overall positive charge $+Q_p$, and due to the overall charge neutrality in the plasma of the envelope there is the buildup of a negative charge $-Q_p$ in a layer close to the star surface some time later given by R/c in which R is the progenitor star radius. The shock wave traverses the envelope in a couple of minutes. In the case of supernova KSN 2011d the shock wave traversed the envelope in less than 20 minutes which means that it had a mean velocity close to that of light. As it will be shown below in detail, at the end of the fast peak seen in the light curve of supernova KSN

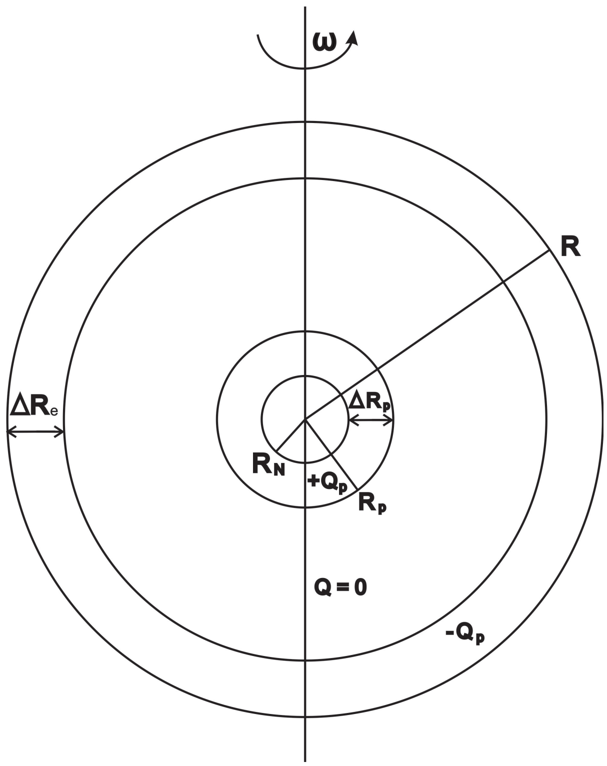

Figure 1. Fig 1. The supernova capacitor formed by two shells with opposite charges and the neutral plasma constituted mainly of protons and electrons. The proto-neutron star with radius R_N lies at the center. The distances are not to scale because R is much larger than R_N and R_p, and as shown below ΔR_p is about twice R_N.

2011d, about 16 min after the shock wave breakout on the star surface, the progenitor star of this supernova became a rotating spherical capacitor as shown in Fig. 1 below, assuming spherical symmetry for simplicity. Actually, as we will see below the spherical capacitor is formed even if the shock wave does not break out on the star surface. It was the case of supernova KSN 2011a.

As the positive and negative charges should be equal, the following relation should hold $\rho_p 4\pi R_N^2 \Delta R_p = \rho_e 4\pi R^2 \Delta R_e$ from which we obtain $\rho_p R_N^2 \Delta R_p = \rho_e R^2 \Delta R_e$. In this expression ρ_p and ρ_e are the electric charge densities of protons and electrons in the positive and negative layers, R_N is the proto-neutron star radius, and ΔR_p and ΔR_e are the thicknesses of the positive and negative layers as indicated in Figure 1.

The formed electric field drives outwards the protons of the envelope and slows down its electrons. Of course, very complex motions occur due to large scale collisions between protons and electrons, but as the proton is about 1835 times more massive than the electron, the protons transfer momentum to the electrons that also, initially, move outwards. The formation of the electric field explains the outward expansion of the envelope since protons carry most of the mass. Of course, the capacitor changes with time because there is repulsion between protons in the positive layer and also repulsion between electrons in the negative layer. Therefore, the thicknesses of both layers should increase over time. This is analyzed in detail below.

Due to the progenitor star rotation there is also the formation of magnetic fields. The electric and magnetic field of a spherical rotating shell with charge $+Q_p$ are given by

$$\vec{E} = \frac{kQ_p}{r^2}\widehat{r} \tag{1}$$

and

$$\overrightarrow{B}(r,\theta) = \frac{\mu_o}{4\pi}\frac{m}{r^3}\left(2\widehat{r}\cos\theta + \widehat{\theta}\sin\theta\right) \tag{2}$$

for $R - \Delta R_e > r > R_p$ as found in many books on Electrodynamics. The magnetic field is the field of a magnetic dipole with magnetic moment $\overrightarrow{m} = \frac{Q_p R_p^2 \omega}{3}\widehat{z}$ which points in the direction of the rotational axis of the progenitor star which can be chosen in the +Z direction. The angular velocity ω is the angular velocity of the positive shell. Of course there is also another magnetic field $\vec{B}_n$ for $r < R_N$ which means for points inside the proto-neutron star. We do not need to deal with this field. And there is yet another magnetic field that acts on the envelope. It is originated from the electrons that are in the upper shell of thickness ΔR_e which is also rotating with velocity ω_e. This rotating negative shell generates a constant magnetic field given by

$$\vec{B} = -\widehat{z}\frac{2\mu_0}{3}\sigma_e R\omega_e = -\widehat{z}\frac{2\mu_o}{3}\frac{Q_p}{4\pi R}\omega_e \tag{3}$$

for $r < R - \Delta R_e$.

This field is much weaker than the field given by Equation (2) because R is much larger than R_N and ω_e is very small compared to ω because as shown by Di Mauro et al. (2016) in red giants the upper layers rotate much slower than the inner layers close to the core. Therefore, we can disregard this field.

The electric field energy density is given by $u_E = \frac{1}{2}\varepsilon_o E^2$ and thus the total electric energy is just the integral $U_E = \int_{R_p}^{R} u_E d\tau$ in which $d\tau$ is the volume element. Therefore, the energy of the electric field is

$$U_E = \frac{1}{8\pi\varepsilon_o}\frac{Q_p^2}{R_p} \tag{4}$$

because $R \gg R_p$. There is also the energy of the electric energy inside the positive layer that can be disregarded because this layer has a very small volume.

The charge Q_p is generated in a very short time just above the proto-neutron star. Of course, the sudden appearance of Q_p generates an electromagnetic wave that sweeps out the star all the way up to its surface. It causes a strong surge of electromagnetic radiation because the ions of the envelope interact with this wave.

This surge in seen in the light curve of supernova KSN 2011d and is the first fast peak that lasted about 16 min. From this we infer that the radius of this supernova is about 411.4 $R_\odot$ which is close to the value of Garnavich et al. (2016) of $(490 \pm 20)R_\odot$ and much larger than the value found by Rubin & Gal-Yam (2017) of about $111R_\odot$. The error bar of the value 411.4 $R_\odot$ depends only on the measurement of the duration of the fast peak and is of the order of ± 51 so that the radius can be given by $(411.4 \pm 51)R_\odot$.

Now we can calculate the order of magnitude of the positive charge Q_p. From the discussion above we should assume that the charge Q_p occupies a small volume with a surface radius much smaller than R and larger than R_N. By using the fact that we should have $U_E \sim 10^{44}$J, which is the typical energy released in a supernova explosion, we find from Equation (4)

$$\frac{Q_p^2}{R_p} = \frac{2U_E}{k} = \frac{2 \times 10^{44}}{9 \times 10^9} \approx 10^{35} \tag{5}$$

in SI units. A star with a radius of $411.4R_\odot$ and a mass $M \approx 15M_\odot$ has about 10^{58} protons and thus the total positive charge is about 10^{39} C. We can find another relation between Q_p and R_p if we suppose that the mass densities (and positive charge densities) in the whole progenitor star and in the positive layer at the time of formation of this layer are of the same order. That is,

$$\frac{Q}{\frac{4\pi}{3}R^3} \sim \frac{Q_p}{\frac{4\pi}{3}\left(R_p^3 - R_N^3\right)} \tag{6}$$

This is a very reasonable assumption because Q_p should be much smaller than Q. If we suppose that $\Delta R_p \ll R_N$ we obtain an inconsistency in the values and this means that ΔR_p and R_N are of the same order. But they can be of the same order such that $R_p^3 \gg R_N^3$. In this case Equation 6 becomes

$$\frac{Q_p}{R_p^3} \sim \frac{Q}{R^3} = \frac{10^{39}}{\left(411.4R_\odot\right)^3} \tag{7}$$

Combining Equations (5) and (7) we obtain $Q_p \approx 10^{20}$C and $R_p \approx 100$km so that $\Delta R_p \approx 70$km which is about twice R_N. We see that $100^3 \gg 30^3$ and so the assumption ${R_p}^3 \gg {R_N}^3$ is very good. The charge $Q_p \approx 10^{20}$C corresponds to 10^{39} protons which is a tiny portion of the total number of protons.

Let us now assess the role of the magnetic field in the expansion of the star envelope. The magnetic field that acts on the charged particles of the envelope is given by the expression

$$\overrightarrow{B} = \frac{\mu_o}{4\pi}\frac{m}{r^3}\left(2\widehat{r}\cos\theta + \widehat{\theta}\sin\theta\right) \tag{8}$$

and thus its intensity is

$$B(r,\theta) = \frac{\mu_o}{4\pi}\frac{m}{r^3}\left(3\cos^2\theta + 1\right)^{1/2} \tag{9}$$

The magnetic energy density is given by $u_B = \frac{B^2}{2\mu_o} = \frac{\mu_o m^2}{32\pi^2 r^6}\left(3\cos^2\theta + 1\right)$ which, integrated in the envelope, yields the magnetic energy

$$U_B = \frac{\mu_o m^2}{32\pi^2}\int_{R_p}^{R}\frac{2\pi r^2 dr}{r^6} \times \int_0^{\pi}\left(3\cos^2\theta + 1\right)\sin\theta d\theta \tag{10}$$

which is equal to

$$U_B = \frac{\mu_o m^2}{12\pi R_p^3} = \frac{\mu_o}{108\pi}Q_p^2 R_p \omega^2 = \frac{\mu_o \pi}{27}\frac{Q_p^2 R_p}{T^2} \tag{11}$$

We have taken into account in the integration of U_B that $R \gg R_p$. If the magnetic energy is very important in the expansion of the envelope than we should have $U_B \sim 10^{44}$ J and from this value we find

$$T^2 = \frac{\mu_o \pi}{27}\frac{Q_p^2 R_p}{10^{44}}$$

which yields $T \approx 10^{-3}$s. This is of the order of the period of the fastest pulsars and is thus too short because it is expected that the positive layer rotates slower than the proto-neutron star. Therefore we conclude that the magnetic field does not play an important role in the expansion of the envelope. This means that protons and electrons do not curve much by the magnetic field and, therefore, their trajectories are almost in the radial direction.

3 EQUATIONS OF MOTION FOR THE CHARGED PARTICLES IN THE ENVELOPE

As was shown above the magnetic field does not play a very important role in the expansion of the envelope (for $R - \Delta R_e > r > R_p$) and thus we can propose the following equation of motion for a proton in the envelope

$$\frac{d}{dt}\left(\frac{m_{op}\vec{v}}{\sqrt{1 - \frac{v^2}{c^2}}}\right) = \frac{kqQ_p}{r^2}\widehat{r} + F_{fp} \tag{12}$$

where m_{op} is the rest mass of the proton and the last term is the frictional force that acts on the proton and $q = 1.6 \times 10^{-19}$ C. Below I will enter into the details of the frictional term. For the electrons in the envelope (for $R - \Delta R_e > r > R_p$) there is a similar equation of motion given by

$$\frac{d}{dt}\left(\frac{m_{oe}\vec{v}}{\sqrt{1 - \frac{v^2}{c^2}}}\right) = -\frac{kqQ_p}{r^2}\widehat{r} + F_{fe} \tag{13}$$

in which m_{oe} is the electron rest mass and the last term is the friction force. For the cases of velocities below

60.000 km/s (0.2c) we can use Newtonian Mechanics and then Equation (12) above becomes

$$m_{op}\frac{dv}{dt} = \frac{kqQ_p}{r^2} - \frac{\alpha_p}{v^2} \tag{14}$$

in which we have used the friction force defined by Callen (2006) when $v < 0.2c$. Below I detail the calculation of α_p. Equation (14) can be easily analyzed. When the velocity increases the frictional term diminishes, and thus $\frac{dv}{dt}$ can become zero. When this happens we have the relation $\frac{kqQ_p}{r^2} - \frac{\alpha_p}{v^2} = 0$ from which we obtain $v = \left(\frac{\alpha_p}{kqQ_p}\right)^{1/2} r$. Let us label the velocity as v_M and the corresponding r as R_M. Hence we have the equation

$$v_M = \left(\frac{\alpha_p}{kqQ_p}\right)^{1/2} R_M \tag{15}$$

I labeled this equation with M because we notice that the time derivative of Equation (14) for $v = v_M$ and $r = r_M$ is negative so that the velocity v_M is maximum. We can calculate the order of magnitude of R_M supposing that v_M should be of the order of 20,000 km/s (typical velocity of the outer layers for supernovae remnants with progenitor stars' masses of about 15 solar masses). From what was deduced by (Callen (2006)), on p. 57, we notice that we can disregard the thermal frequency for electron-proton collisions because the proton mass is much larger than the electron mass. Thus, we can use only the proton-proton thermal frequency from (Callen (2006)) given by

$$\bar{\nu}_{pp} = \frac{\sqrt{2}}{3\sqrt{\pi}} n_p \frac{e^4}{(4\pi\varepsilon_o)^2} \frac{4\pi}{m_p^{1/2}\left(\frac{1}{2}m_p v^2\right)^{3/2}} \frac{1}{\sqrt{2}} \ln\Lambda_p \tag{16}$$

in which n_p is the proton density in the star envelope. Of course Equation (16) is only valid for speeds below 0.2c. As shown by (Callen (2006)) thermal effects have been taken care of in the deduction of Equation (16) above by means of a Maxwellian distribution of velocities. As electrons are very light and the density in a red giant envelope is about 0.1kg/m3 we have $n_p = \rho/m_p = 0.1/1.67 \times 10^{-27} = 5.9 \times 10^{25} m^{-3}$, and from the cited reference above, on page 62, we have that $\ln\Lambda_p \sim 15$. We obtain, then, $\bar{\nu}_{pp} \approx \frac{10^{26}}{v^3}$ in SI units. The friction force is given by equation 3.130 in the cited reference above modified for proton-proton collisions

$$F_f = -\bar{\nu}_{pp} m_p v \approx -\frac{0.1}{v^2} \tag{17}$$

from which we obtain $\alpha_p \approx 0.1$Nm2/s2. Using this value in Equation (15) and assuming that $v_M \sim 20,000$km/s we obtain $R_M \sim 2.4 \times 10^{13}$m. This is about 100 times the progenitor star radius. Of course the photosphere will have, then, about this radius.

4 IMPORTANT PROOF ON THE CORRECTNESS OF THE MODEL

Considering an average velocity of 10,000 km/s for the protons in the envelope we grasp that the distance is reached after a time given by $t_M = {}^{10^{13}}/_{10^7} = 10^6$s =12 days since the beginning of the explosion. As the protons and electrons in the envelope are accelerated by the electric field of the capacitor they generate electromagnetic radiation produced by the fields (in the radiation zone or far field zone)

$$E(r', \theta, t) = \frac{qa\sin\theta}{4\pi\varepsilon_o c^2 r'} e^{i(\vec{k}.\vec{r'} - \omega t)}$$

and

$$B(r', \theta, t) = \frac{qa\sin\theta}{4\pi\varepsilon_o c^3 r'}$$

which are perpendicular to each other. The angle θ is the angle between the position of the charge $\vec{r'}$ and the outwards radial direction. In the above equations a is the acceleration of the charge. The total radiated power by each particle is given by Larmor's formula

$$P = \frac{1}{6}\frac{\mu_o q^2 a^2}{\pi c}$$

This radiation is absorbed by atoms of the envelope and the emitted light is generated, of course, by the de-excitation of the atoms.Taking a look at Equation (14) we see that the acceleration decreases as r increases, that is, over time, and when the acceleration decreases the radiated power decreases and also the absorption of the radiation by atoms, and as a consequence, the de-excitation of atoms. This is inline with the existence of a plateau in the light curve after a couple of days since the beginning of the explosion. Therefore, we expect the plateau of the light curve to occur at the time t_M when $a = 0$, that is, when v_M and R_M are related by Equation (15). As calculated above $t_M \approx 12$days since the beginning of the explosion. And now let us observe the light curve of KSN 2011d which is found in many references. For example, in Garnavich et al. (2016), on p. 3, we notice that the light curve plateau happens, indeed, around (13-14) days that is very close to 12 days.

5 MOTION OF HYDROGEN ATOMS IN THE ENVELOPE

After the completion of the capture of most electrons by protons the plasma is turned into a hydrogen gas. And upon neutral hydrogen atoms the electric field ceases to act but the hydrogen atoms continue with the protons high speeds which are slowed down by collisions, that is, the equation of motion of a hydrogen atom becomes

$$\frac{d}{dt}\left(\frac{m_{op}\vec{v}}{\sqrt{1-\frac{v^2}{c^2}}}\right) = -\beta v^2 \widehat{r} \tag{18}$$

Of course the friction force exists in this case because of collisions. As the plasma is transformed into a hydrogen gas and the hydrogen atoms have high speeds we have now a dragging force acting on hydrogen atoms in a hydrogen gas which for high speeds should be proportional to v^2 as is the case for neutral particles at high speeds in a gas. Let us take a look at the hydrogen motion for speeds below 60.000 km/s because it is described by the simple equation

$$m_{op}\frac{dv}{dt} = -\beta v^2 \tag{19}$$

whose solution is

$$v(t) = \frac{v_i}{\left(1 + \frac{v_i\beta}{m_{op}}t\right)} \tag{20}$$

which is a decreasing function of time. As discussed above the initial velocity v_i are in the range (10,000-20,000) km/s and is the velocity of a hydrogen atom at a point inside the expanding envelope. Let us verify if this equation above for $v(t)$ agrees with the published data. Let us use the data from two different supernovae from two different articles. In Hearnshaw et al. (1988) there are data on the expansion velocity of SN 1987a over time measured by means of the $H\alpha$ absorption. The data are shown in Fig. 3 on p. 101. Upon fitting the data of Fig. 3 of the cited reference to Equation (20) we find $\beta = (7.7 \pm 0.5) \times 10^{-41}$kg/m or equivalently $\frac{\beta}{m} = (4.6 \pm 0.3) \times 10^{-13}$m-1 . In Takáts & Vinkó (2012) there are data on the expansion velocities of a couple of supernovae. For supernova SN 2005cs the data are displayed in Figure 4, top left. The best fitting of the data to equation 17 yields $\beta = (9.5 \pm 1.8) \times 10^{-41}$ kg/m and $\frac{\beta}{m} = (5.7 \pm 1.1) \times 10^{-13}$ m-1. We notice that the values of β for the two supernovae are close.

6 THE EXPANSION OF THE POSITIVE LAYER

Once there is the buildup of the positive layer protons begin repelling each other. They move radially due to the electric field generated by the positive layer. Let us consider a proton at a position $r > R_p$ inside the positive layer. It is subjected to the electric field

$$E(r) = \frac{4\pi k\rho}{3}\left(r - \frac{R_p^3}{r^2}\right) \tag{21}$$

and, thus the force $F(r) = \frac{4\pi k\rho q}{3}\left(r - \frac{R_p^3}{r^2}\right)$ acts on the proton. Therefore, disregarding magnetic field effects, its equation of motion is described by

$$\frac{d}{dt}\left(\frac{m_{op}v}{\sqrt{1-\frac{v^2}{c^2}}}\right) = \frac{\rho}{3\varepsilon_o}\left(r - \frac{R_p^3}{r^2}\right) \tag{22}$$

in which we disregarded the friction force because as protons repel each other the protons do not move much through the positive layer. This equation can be written as

$$m_{op}\left(\gamma + \gamma^3\frac{v^2}{c^2}\right)\frac{dv}{dt} = \frac{\rho}{3\varepsilon_o r^2}\left(r^3 - R_p^3\right) \tag{23}$$

As $R_p < r$, $\frac{dv}{dt} > 0$ and as R_p should increase over time due to the initial velocities of protons should be positive when r increases which is exactly the expected behavior. Therefore, the positive layer thickness increases over time. We can see this better for $v < 0.2c$because in this case the above equation becomes

$$m_{op}\frac{dv}{dt} = \frac{\rho}{3\varepsilon_o}\left(r - \frac{R_p^3}{r^2}\right) \tag{24}$$

whose left side can be written as

$$m_{op}\frac{dv}{dr}v = \frac{\rho}{3\varepsilon_o}\left(r - \frac{R_p^3}{r^2}\right) \tag{25}$$

which when integrated with initial conditions $r = r_i$ and $v = v_i$ yields

$$\frac{1}{2}m_{op}v^2 - \frac{1}{2}m_{op}v_i^2 = \frac{\rho}{6\varepsilon_o}\left(r^2 - r_i^2\right) + \frac{\rho R_p^3}{3\varepsilon_o}\left(\frac{1}{r} - \frac{1}{r_i}\right) =$$

$$\frac{\rho}{6\varepsilon_o}\left(r - r_i\right)\left[\frac{\left(r + r_i\right)rr_i - 2R_p^3}{rr_i}\right]$$

whose right side is always positive because $r > r_i$ and $R_p < r$ and $R < r_i$. Therefore, $v > v_i$ and all this means that the positive layer expands. The motions of all protons and electrons in the envelope can be simulated with the use of a lot of computing making use of a Maxwellian velocity distribution for the protons and electrons to take into account the effect of the temperature. It requires calculations with supercomputers that I do not have. Therefore, this goes beyond the scope and purpose of this article that only aims at showing that the expansion of the envelope is caused by the action of a powerful electric field. And this we clearly see by means of the equations of motions of protons and electrons.

7 ASYMMETRY IN SUPERNOVAE EXPLOSIONS

All core-collapse supernovae explosions should be asymmetric. This is inferred from the supernovae remnants that in general have the shape of an oblate ellipsoid. This can be easily understood as a consequence of rotation of the progenitor star. When the radiation pressure becomes insufficient to balance the gravitational pull towards the center of the progenitor star, its inner layers begin to fall towards the center. These falling layers are rotating when they begin to fall. Therefore, the generated shock wave has an ellipsoidal shape and when it bounces back at the star core it continues to be ellipsoidal. But when the proto-neutron star is formed it becomes spherical quickly so that when the shock wave hits it, the transmitted shock wave that penetrates into the envelope plasma and generates the positive layer should have an ellipsoidal shape, and therefore, the positive layer should have an ellipsoidal shape so that the capacitor is a rotating ellipsoidal capacitor instead of a rotating spherical capacitor. But the effect of asymmetry on the envelope expansion should be small because the electric field generated by an ellipsoidal shell is of the same order of the electric field given by the formulas above if the ellipsoid is not too oblate. In this line Leonard et al. (2006) proposes that the asymmetry in supernovae may be a universal characteristic of all supernovae explosions.

8 THE HOLLOW SHELL

As we saw above the protons in the envelope and in the positive layer have radial outward motions due to the action of electric fields. Therefore, as they move outward there is the development of a region devoid of matter around the proto-neutron star. This is a very well-known fact. According to Jones et al. (1998) "Shell-type remnants, which represent almost 80% of the 215 SNRs cataloged in our Galaxy, depict a hollow morphology in radio wavelengths, . . . " We should investigate if these 80% remnants are all from core-collapse supernovae.

9 THE ORIGIN OF THE MAGNETIC FIELD SEEN IN SUPERNOVAE REMNANTS

There have been many reports of radial and tangential magnetic fields in the remnants of supernovae Fürst & Reich (2004), Jun & Norman (1996), Dickel & Milne (1976), Cowsik & Sarkar (1980), Milne et al. (1989). Radial magnetic fields have been identified in young remnants and older remnants have more peripheral magnetic fields. However, there is not much data on magnetic fields in supernovae remnants as recognised by Dickel & Milne (1976) in the introduction of their article. As stated by Jun & Norman (1996) "The origin of radial B-fields in young SNRs, however, has remained a mystery." We grasp now their origin and it means that the currents generated by the charges $+Q_p$ and $-Q_p$ continue to exist for quite some time along the expansion of the envelope. In Equation (9) we see that the intensity of the magnetic field is of the order of

$$B(r) \approx \frac{\mu_o}{4\pi}\frac{m}{r^3} = \frac{\mu_o Q_p R_p^2 \omega}{4\pi r^3}$$

from which we obtain that

$$B(r) \approx 10^{23}\frac{\omega}{r^3}$$

in Teslas. Unfortunately in the literature we do not find data with the values of B versus r in supernovae remnants. If we had we could assess the order of magnitude of ω. There is one more complication in the measurement of the magnetic field: The total magnetic field at a certain point in the envelope or outside of it will include the magnetic field generated by the neutron star.

10 UNDERSTANDING THE DIFFERENT EJECTA VELOCITIES IN SUPERNOVAE REMNANTS

According to what was shown above there should be 3 different velocities in the ejecta of young remnants which are a velocity associated with the expansion of the negative layer, a velocity of the hydrogen atoms of the envelope and a velocity associated to the protons of the positive layer. This is expected to change over time as the protons of the positive layer travel through the hydrogen gas of the envelope and because of interactions between layers. Hearnshaw et al. (1988), on page 100, have indeed reported three expansion velocities for SN1987A remnant at t=200 days from the analysis of hydrogen emission lines. Lopez & Fesen (2018) report also that "In terms of kinematics Cas A is composed of three distinct sets of ejecta."

11 SIGNATURE OF THE NEGATIVELY CHARGED LAYER

There are plenty of signatures of the accelerated electrons in the outer layers of the expanding envelope. For example, as stated by Lopez & Fesen (2018) "Several young SNRs (e.g., SN 1006, Tycho, and RCW 86), emit synchroton emission in narrow filaments around their periphery. This synchroton emission results from a non-thermal population of electrons, accelerated to relativistic energies behind the shock, spiraling around an amplified post-shock magnetic field. There are many open questions in this process: under what conditions do shocks efficiently accelerate particles?" Of course, the author did not refer to the initial shock wave that lasts a very short time, but to the boundary between the remnant and the interstellar space.

12 THE SUPERNOVA CAPACITOR IS A POWERFUL PARTICLE ACCELERATOR

The potential difference between the positive and negative layers at the moment of their formation in KSN 2011d is

$$V = \frac{kQ_p}{R} = \frac{9 \times 10^9 \times 10^{20}}{411.4R_\odot} = 3 \times 10^{18}$$

in Volts and therefore, the gamma rays generated by bremsstrahlung radiation can reach energies of up to 4.8×10^{18} eV=48,000 TeV. Of course, this value is an upper limit. Amenomri & others (The ASγ Collaboration) (2021) state “Here, we report the observation of gamma-ray emission from the supernova remnant G106.3+2.7 above 10 TeV." Vink (2004) also that in shell-type supernova remnants, and gives the example of SN 1006, data from X-ray emission dominated by synchroton radiation have shown that electrons are accelerated up to 100 TeV. There have also been reports of gamma emissions in lower energies of up to a couple MeV Clayton & The (1991).

13 CONCLUSION

I have presented a new mechanism for the explosion of core-collapse supernovae which is very consistent theoretically and is in good agreement with important observations and data from core-collapse supernovae. The basis for the mechanism is the gigantic capacitor that is generated as a consequence of the interaction of the shock wave at the interface between the proto-neutron star and the envelope plasma. Maybe we could name the capacitor as the supernova capacitor which is almost a spherical capacitor. For the first time we have a model that links the shape, the light curve and the ejecta velocities of a supernova to its dynamics. We can investigate further if the mechanism is valid for Type Ia supernovae. In this case it would have a universal character. Using the above mechanism and a lot of computing it is expected that the overall expansion of the envelope of the star can be simulated.

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