Physics International 5 (1): 36-44, 2014
ISSN: 1948-9803

doi:10.3844/pisp.2014.36.44 Published Online 5 (1) 2014 (http://www.thescipub.com/pi.toc)

NUCLEAR DETONATION AROUND COMPACT OBJECTS

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Received 2014-02-05; Revised 2014-03-17; Accepted 2014-03-24

ABSTRACT

In this study we explore the various aspects involved in nuclear detonations occurring around compact objects and the energetics involved. We discuss the possibility of sub-Chandrasekhar white dwarfs detonating due to the buildup of a layer of hydrogen on the CO white dwarf by accreting from a companion star to explain observed deviations such as subluminous type Ia. We also detail some of the energetics involved that will make such scenarios plausible. Also an alternate model for gamma ray bursts is suggested. For a very close binary system, the white dwarf (close to Chandrasekhar mass limit) can detonate due to tidal heating, leading to a supernova. Material falling on to the neutron star at relativistic velocities can cause its collapse to a magnetar or quark star or black hole leading to a gamma ray burst. As the material smashes on to the neutron star, it is dubbed the Smashnova model. Here the supernova is followed by a gamma ray burst.

Keywords: Nuclear Detonation, Compact Objects, Subluminous Type Ia SN, GRB, Smashnova

1. INTRODUCTION

Compact objects, such as White Dwarfs (WD), Neutron Stars (NS) and Black Holes (BH), are stellar remnants and at the end-point of stellar evolution, when most of their nuclear fuel is exhausted. White dwarfs no longer burn nuclear fuel; they are slowly cooling as they radiate away their residual thermal energy, balancing gravitational pressure with electron degeneracy pressure. If the white dwarf accretes mass, then temperature increases due to increase in the increase in the gravitational pressure. This could result in igniting hydrogen or carbon thermonuclear reaction. The ignition may occur if the reaction time is shorter than the time of cooling process (such as neutrino loss or convection). The time of the thermonuclear reaction at the white dwarf centre becomes shorter than the typical convection time when the temperature exceed $\sim 3\times10^7 K$ for hydrogen burning, $\sim 2\times10^8 K$ for helium burning and $\sim 7\times10^8 K$ for carbon burning.

2. ASPECTS OF NUCLEAR BURNING AROUND COMPACT OBJECTS

2.1. White Dwarfs

The height of the layer (on the WD) required to heat hydrogen to this temperature (T_H) is:

$$h \approx \frac{R_g T_H}{g_{WD}} \sim 25km \qquad (1)$$

where, $g_{WD} \approx 109\ cm/s^2$ is the acceleration due to gravity on the WD. (where $R_g \approx 10^8 \approx ergs/g$ is the gas constant)

The mass of the H layer is given by Equation 2

$$M_H = \left(4\pi R_{WD}^2 h\right)\rho \approx 2\times10^{30} g \sim 10^{-3} M_{sun} \quad \left(where, \rho \sim 10^5 g/cc,\ R_{WD} \sim 6\times10^8 cm\right) \qquad (2)$$

The energy released during this process is $\sim 6\times10^{18} ergs/g$. The velocity with which this mass is ejected is given by Equation 3:

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$$M_H\left(6\times10^{18}\right)=\frac{1}{2}M_H v^2$$
$$v\approx3\times10^{9}\,cm/s \tag{3}$$

And the corresponding energy released is given by Equation 4:

$$\frac{1}{2}M_H v^2\approx10^{49}\,ergs \tag{4}$$

White dwarfs cannot attain the temperature required to initiate carbon burning. But once the reaction starts, it can sustain and even increase the temperature which could be high enough to ignite helium and carbon. If ε is the energy released per unit mass then Equation 5:

$$MR_gT=M\varepsilon$$
$$T=\frac{\varepsilon}{R_g} \tag{5}$$

In the case of H burning, even if a fraction (say 1%) of the energy goes into increasing the temperature, this works out to be Equation 6:

$$T=\frac{0.01\varepsilon}{R_g}\sim7\times10^{8}K \tag{6}$$

This is high enough to ignite carbon.

2.2. Neutron Stars

In the case of the neutron stars, since the surface gravity on them ($g_{NS}\approx10^{15}cm/s^2$) is higher, the carbon burning temperature can be attained. The height of the layer on the neutron star required to heat hydrogen, helium and carbon to their respective burning temperature is Equation 7 to 9:

$$h\approx\frac{R_gT_H}{g_{NS}}\sim2cm \tag{7}$$

$$h\approx\frac{R_gT_{He}}{g_{NS}}\sim20cm \tag{8}$$

$$h\approx\frac{R_gT_C}{g_{NS}}\sim60cm \tag{9}$$

The mass of the C layer on the neutron star is given by Equation 10:

$$M_H=\left(4\pi R_{NS}^2h\right)\rho\approx2\times10^{27}g\sim10^{-6}M_{sun} \tag{10}$$

(where, $\rho\sim10^{13}g/cc,\ R_{NS}\sim2\times10^{6}cm$)

The energy released during this process is *~9×10^17 ergs/g*. The velocity with which this mass is ejected is given by Equation 11:

$$M_H\left(9\times10^{17}\right)=\frac{1}{2}M_H v^2$$
$$v\approx10^{9}\,cm/s \tag{11}$$

And the corresponding energy released is given by Equation 12:

$$\frac{1}{2}M_H v^2\approx10^{45}\,ergs \tag{12}$$

2.3. Black Holes

High temperatures can also be produced in the accretion disks around black holes. The temperature of the disk corresponding to the Eddington luminosity can be obtained as Equation 13:

$$4\pi R^2\sigma T_D^4=\frac{4\pi GMm_Pc}{\sigma_T} \tag{13}$$

where, $R=fR_S;\ R_S=\frac{2GM}{c^2}$ is the Schwarzschild radius and typically $f\sim3$, below which there will be relativistic instabilities. This gives the disk temperature as Equation 14:

$$T_D=\left[\left(\frac{c^5}{G}\right)\left(\frac{m_P}{M}\right)\left(\frac{1}{\sigma\sigma_T}\right)\left(\frac{1}{4f^2}\right)\right]^{1/4} \tag{14}$$

The disk temperature depends inversely with black hole mass, hence nuclear burning can be achieved only around lighter black holes. For a 3.8 solar mass black hole (J1650, the smallest observed black hole), this temperature corresponds to that of hydrogen burning ($\sim3\times10^7K$).

Once this reaction starts, it can sustain and increase the temperature which could be high enough to ignite helium and carbon as given by Equation 5 and 6.

Another possible way by which higher temperatures can be achieved is when tidal break up of compact objects like white dwarfs or neutron stars occur around the black hole. The mass of the black hole required for the tidal break up (at about a distance of ten times the Schwarzschild radius) is given by Equation 15:

$$M_{BH}=\left[\left(\frac{20G}{Rc^2}\right)^3\left(\frac{M}{4}\right)\right]^{-1/2} \tag{15}$$

For a typical white dwarf, this works out to $\sim 5\times10^3 M_{sun}$. The corresponding binding energy released is given by: $\frac{3}{5}\frac{GM^2}{R} \sim 10^{51} ergs$.

In the case of a neutron star the black hole mass required for its tidal break up $\sim 10 M_{sun}$. The corresponding binding energy released $\sim 10^{54} ergs$. This could be a possible scenario for short duration gamma ray bursts.

3. SUBLUMINOUS TYPE IA SUPERNOVAE

Type Ia supernovae form the highest luminosity class of supernovae and are consequently used as distance indicators over vast expanses of space-time, i.e., over cosmological scales. They are used commonly as the brightest standard candles as they are thought to result from thermonuclear explosions of carbon-oxygen white dwarf stars (Hoyle and Fowler, 1960). These explosions arise when the C-O WD accretes material from a companion star and is pushed over the Chandrasekhar limit causing it to collapse gravitationally and heat up to carbon detonation temperature.

The degeneracy (i.e., high density of C and O nuclei) accelerate the reaction rate so that the entire white dwarf can be incinerated and disintegrated resulting in about 0.5-1.0 solar mass of Ni-56, which subsequently undergoes two consecutive beta decays (6 days to Co-56 and 77 days to Fe-56), the exponential decay of these isotopes then powering the light curve for a few months releasing at least 10^{42}-10^{43}J in the optical band. These models (Kasen *et al*., 2009; Mazzali *et al*., 2007) generally explain the observed properties, with notable exceptions like the sub-luminous 1991 bg type of SN (Leibundgut *et al*., 1993).

It has also been debated whether all progenitors of SN Ia are single white dwarfs pushed over the limit. Mergers of WDs (in a binary, for e.g., white dwarf binaries with 5 min orbital periods are known) could give rise to SN Ia (Webbink, 1984; Iben and Tutukov, 1984).

However some calculations did not result in an explosion (Stritzinger *et al*., 2006; Saio and Nomoto, 1985). More recently it was suggested that merger of equal mass WDs could lead to sub-luminous explosions (Pakmor *et al*., 2010). Again in such sub-luminous explosions, the C-O nuclei would not be expected to be completely converted to mostly Ni-56. For instance isotopes like Ti-50, are supposed to be primarily produced in such so called sub-Chandrasekhar SN Ia (Hughes *et al*., 2008). In such collapses electron captures may dominate to produce neutron rich nuclei like Ti-50.

We also have the recent example of SN2005E, which showed presence of about 0.3 solar mass of Calcium (most Calcium rich SN), which is an intermediate stage in the production of Ni. So this is an example of incomplete silicon burning occurring in low density C-O fuel for a range of temperatures. The density of a WD scales as the mass, M squared, i.e., $\rho \propto M^2$.

A very large number of white dwarfs are known to have a mass substantially lower than a solar mass (Sivaram, 2006). Is there any way these sub-Chandrasekhar WDs could detonate?

3.1. Double Detonation of Sub-Chandrasekhar White Dwarfs

One way could be to build up a layer of helium on the C-O WD by accreting from a helium rich companion star, i.e., a hydrogen deficient star with an extensive He atmosphere. The helium layer would first detonate at $\sim 2\times10^8 K$ releasing enough energy to heat the C-O nuclei to $7\times10^8 K$ to initiate C-burning, which would incinerate a sub-Chandrasekhar WD. The lower progenitor mass would then give rise to a sub luminous SN type Ia.

Here we detail some energetic of the phenomena which would make such scenarios plausible. For instance, a 0.6 solar mass WD would have a gravitational binding energy of $\sim 7\times10^{49} ergs$. As one gram of carbon, undergoing nuclear detonation releases $\sim 9\times10^{17} ergs$, 10^{32} g of carbon must detonate to form Ni-56 to disintegrate the white dwarf. This mass is ~0.05 solar mass. To detonate carbon, the temperature required is $7\times10^8 K$. The required energy to heat the WD to this temperature is Equation 16:

$$MR_g T \approx 7\times10^{49} ergs \quad (16)$$

The helium layer which forms on the WD must be heated to a temperature of $2\times10^8 K$ to trigger helium burning. The height of the layer (on the WD) required to heat the helium to this Temperature (T_{He}) can be obtained from Equation 1 as $h \sim 3\times10^7 cm$. The mass of the He layer is Equation 17:

$$M = 4\pi R^2 h\rho \approx 2\times10^{31} g \sim 0.01 M_{sun} \quad (17)$$

As the helium nuclear reaction releases $\sim 3\times10^{18} ergs/g$, the detonation of the helium layer (on reaching its reaction temperature) would release an energy of $\sim 6\times10^{49} ergs$, which is sufficient to heat the C-WD, to the required temperature for carbon burning. So this double detonation mechanism, first of the helium layer accumulating on the WD and followed by detonation of the sub-Chandrasekhar C-O WD, could result in a sub-luminous type Ia SN.

A lower mass He layer could detonate an even lower mass C-O WD and a heavier mass He-shell can detonate a heavier WD. For 1.3 solar mass WD, we need a 0.1 solar mass layer, since the gravitational binding energy scales as $M^{7/3}$.

The collapse time scale for the WD is about a second but as the reactions have much shorter time scales, the explosions of the WD is inevitable. Our analytical results are in agreement with numerical calculations of other authors. (Fink *et al*., 2010)

3.2. Collapse of 'Super Chandrasekhar' White Dwarf

One can also consider a situation when a white dwarf close to the Chandrasekhar limit acquires such a helium layer or debris from an accretion disc (or tidal disruption of a low mass object), falls onto the WD (Sivaram, 2006). The WD, in this case, which may be 'Super Chandrasekhar', would collapse, but the temperature to which it would be heated up (as the energy released scales as $M^{7/3}$) would be substantially higher than the required $7\times10^8 K$ for carbon detonation.

There would also be now losses due to the photo-neutrino process which scales at least as T^8. So even if the WD mass is 10% higher than the limit, the neutrino energy loss would increase by a factor of three or more (T would go up by $M^{4/3}$, so the loss rate would increase as M^{11}) (Sivaram, 1993). So rather than the detonated disintegration of the WD, we would have the collapse of the WD, followed by e-capture by the heavier nuclei, leading to a neutron star.

Moreover, there is a general relativistic induced instability in the collapse of WD's (above the mass limit). This sets in at about 250 times the Schwarzschild radius (Shapiro and Teukolsky, 1982) (i.e., at <1000 km). This would inevitably lead to collapse to a NS for a super-Chandrasekhar WD (rather than a nuclear detonation induced fragmentation).

4. SMASHNOVA

The phenomenon of one celestial body smashing into another is quite common. This process on all scales can be very energetic. Recent example in the solar system is that of the comet shoemaker-levy, that slammed into Jupiter (Molina and Moreno, 2000). The fragments measuring 3 km across released 6 million megatons of energy (this is equivalent to one Hiroshima bomb going off every second continuously for 10 years).

If a planet of Earth's mass collides with Jupiter (Zhang and Sigurdsson, 2003), we can observe extreme UV-soft X-ray flash for several hours and bright IR glow lasting for several thousand years. In dense stellar clusters, like globular cluster, star collisions are not uncommon. The origin of the blue stragglers in old stellar populations is due to merging of 2 or maybe 3 MS stars of 0.8 solar mass. Perhaps about half the stars in central regions of some GC's underwent one or two collisions, over a period of 10^{10} years (Zwart *et al*., 2010).

In R136 cluster of Tarantula nebula, there are more than 10^7 stars in a region less than a parsec. There are many examples of celestial bodies colliding. The collision of galaxies has been studied for long. The Milky Way and Andromeda galaxies are approaching each other at ~300 km/s. They are due for collision in another 3 billion years.

White Dwarf binary with less than 5 min period merges in a few thousand years. Neutron star-white dwarf binaries with periods, 11 and 10.8 min are also observed which will undergo merger (Tamm and Spruit, 2001; Chen and Li, 2006).

4.1. Head-on Collisions

If a white dwarf smashes into a Main-Sequence (MS) star like the Sun, we need to know the signatures. The incoming velocity is ≥700*km/s*. The massive shock wave would compress and heat the sun. The time taken for the 'smash up' is about 5000 s (about an hour). The tidal energy released is given by Equation 18:

$$\frac{3GM_{WD}M_{sun}R_{sun}}{d^2} \sim 10^8 K \quad (18)$$

Due to the impact the nuclear reactions will become much faster. In about an hour, Sun would release thermonuclear energy of about 10^{49}*ergs*, as much energy as it would release in 2×10^8 years. On an average it will be about 3×10^{45}*ergs/s*. The instabilities would blow the sun apart in a few hours. The white dwarf being much denser would continue on its way.

If a white dwarf impacts a Red Giant (RG), it would take about 2 months to penetrate the bloated RG. The RG would collapse, becoming another WD. If the white dwarfs merge, it can form a neutron star. This will release about 10^{53}*ergs* of binding energy. NS impacting a RG or Red Super-Giant (RSG) can cause a SN outburst first followed by collapse of NS and the in-falling material into a black hole and hence leading to GRB. NS colliding with a WR star will result in SN followed by GRB, as the core collapses to a BH.

Black holes in a certain mass range can tidally disrupt a neutron star (Sivaram, 1986), leading to a 1053ergs GRB. In the case of WD and NS close binary, the WD can be tidally stretched or broken up when the separation is about R_{WD}. CO white dwarf (close to N_{ch}) can detonate due to heating. Tidal energy of the order of 10^{50}*ergs* can heat WD to about 10^9K.

This is enough to detonate C and this can hence lead to a SN. Enough material falls on NS at velocities greater than about 10% the speed of light. About $5\times10^{32}g$ of matter falling in has a kinetic energy of ~10^{52}*ergs*. On impact, gamma rays of nuclei energy ≥1*MeV* is released with more than 10^{52}*ergs* in γ-ray photons.

Neutron stars can be spun up and the flux squeezing can increase the magnetic field. When NS slows down due to dipole radiation (Magnetar), in-falling matter can make it collapse to a BH releasing more than 10^{53}*ergs*, with the acceleration of particles due to the magnetic field. Tidal stretching and heating can considerably increase thermonuclear (detonation) rates, especially carbon burning. This process is strongly dependent on the temperature.

The Zeldovich number is given by Equation 19:

$$Z_e = \frac{T_{crit}}{T_b}\left(\frac{T_b - T_u}{T_b}\right) \quad (19)$$

where, T_{crit} is the triggering temperature. T_b and T_u are the burnt and un-burnt material temperatures respectively. For a $z_e\approx10$, we have peaked energy generation rates.

The flame speed is related to Markstein number, which is given by Equation 20:

$$V_F = \left(\frac{\sigma_b}{(C_p)^2}\ \frac{aX^2_{Fu}}{T_{crit}}\ e^{\frac{-T_{crit}}{T_b}}\right) \quad (20)$$

where, σ_b, σ_p are the conduction and specific heat.

When convecting WD reaches density of $3\times10^9 g/cm^3$ and temperature of T = 7×10^8K, the ignition turns critical (Kuhlen *et al*., 2003; Niemeyer, 1999). Nuclear energy generation time scale is comparable to convective turnover time (100 s) and order of sound travel time ~10 s (over a scale height of about 500 km). Flame has a laminar speed and buoyancy (Khokhlov *et al*., 1997); the convection speed is of the order of $10^2 km/s$. The material is accelerated due to the off centre ignition. One solar mass can become convective Equation 21 to 23:

$$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + \alpha(Or)\,{}^{12}C + {}^{12}C \rightarrow {}^{24}Mg$$
$$\dot{\varepsilon}_{nuc} \approx 10^{25}\times5\times n\left({}^{12}C\right)\left(\frac{\rho}{10^9}\right) f_{es} r_{12_C}\, ergs/g/s \quad (21)$$

Where:

$$r_{12_C} \approx 7\times10^{-16}\left(\frac{T}{7\times10^8}\right)^{30} \quad (22)$$

$$f_{es} \approx 10^3\left(\frac{\rho}{10^9}\right)^{2.4}\left(\frac{T}{7\times10^8}\right)^{-7} \quad (23)$$

Therefore, we have Equation 24:

$$\dot{\varepsilon}_{nuc} \approx 3\times10^{13}\left(\frac{T}{7\times10^8}\right)^{23}\left(\frac{\rho}{10^9}\right)^{3.3} ergs/g/s \quad (24)$$

The nuclear specific energy due to the reaction is of the order of $5\times10^{17}n$ (^{12}C)*ergs/g*, where, $n(^{12}C)$ is the fraction of ^{12}C. The specific heat is due to ions, electrons and radiation. It is given by, (Alastuey and Jancovici, 1978; Porter and Woodward, 2000; Kraichnan, 1962) Equation 25:

$$C_P = \frac{3N_A k_B}{2\bar{A}} + \frac{\pi^2 k^2}{\left(\rho_f \big/ mc\right) m_e c^2}\rho N_A Y_e T + \frac{4aT^3}{\rho} \quad (25)$$

The temperature and density are given by Equation 26:

$$T = 7\times10^8 K, \rho = 2\times10^9 g/cc \quad (26)$$

Therefore the specific heat is given by, $CP\approx10^{15} ergs/g10^8K$. For $T = 7\times10^8K$ Equation 27:

$$\tau_{nuc} = \frac{C_P T}{24\dot{\varepsilon}_{nuc}} \approx 10\left(\frac{7\times10^8}{T}\right)^{22}\left(\frac{10^9}{\rho}\right)^{3.3} s \quad (27)$$

The pressure is given by Equation 28 to 34:

$$P = k\rho^{4/3} = 10^{27}\left(\frac{\rho}{2\times10^9}\right)^{4/3} dyne/cm^2\, \eta = r/a \quad (28)$$

where, $a = \left(\frac{k}{\pi G\rho_0^{2/3}}\right)^{1/2} \approx 400km$.

$$M(r) \approx \frac{4}{3}\pi r^3 \rho_0\left(1 - \frac{3}{10}\eta^2\right) \quad (29)$$

$$\rho(r)=\rho_0\left(1-\frac{1}{2}\eta^2\right)(\text{Polytropic index}) \quad (30)$$

$$\frac{dP}{dr}=-\frac{GM(r)}{r^2}\rho(r) \quad (31)$$

$$\frac{dT}{dr}=\left(1-\frac{1}{\Gamma}\right)\frac{T}{P}\frac{dP}{dr} \quad (32)$$

$$T(r)=T_0\left[1-10^{-2}\left(\frac{\rho}{2\times10^9}\right)^{2/3}\left(\frac{r}{10^7}\right)^2\left(1-\frac{1}{15}\eta^2\right)\right] \quad (33)$$

$$L=4\pi\int\dot{\varepsilon}_{nuc}\rho r^2dr=10^{45}ergs/s\left(\frac{\rho}{2\times10^9}\right)^{4.3}\left(\frac{T}{7\times10^8}\right)^{23}\int\left(\frac{r}{10^7}\right)^2(1-f(n)) \quad (34)$$

The size of the region (Timmes, 2000) is about 150 km with density ρ = $2\times10^9 g/cc$. For a recent review of the parameters see Hillebrandt and Niemeyer (2000). The heat flux is Equation 35 to 37:

$$Q(r)=\frac{C(r)}{4\pi r^2}=\frac{\rho}{2}v_{conv}C_P\Delta T \quad (35)$$

$$v_{conv}=\left(\frac{2g\Delta\rho}{\rho}\right)^{1/2}t^{1/2}\approx\left(\frac{4\varepsilon rPL}{3C_PT}\right)^{1/3} \quad (36)$$

$$\Delta T\approx\left(\frac{2Q^2T}{\rho^2C_P^2gl\Delta P}\right)^{1/3}\approx 50km/s\left(\frac{7\times10^8}{T}\right)^{1/3}\left(\frac{L}{10^{45}}\right)^{1/3} \quad (37)$$

The conduction Equation 38 to 43:

$$\sigma=\frac{4acT^3}{\rho k} \quad (38)$$

$$\eta=\frac{10^9}{Z}\left(\frac{\rho}{10^9}\right)\approx10^9 g/cm/s \quad (39)$$

$$\mathrm{Re}\approx\frac{\rho v_{conv}l}{\eta}=10^{14} \quad (40)$$

$$\mathrm{Pr}\approx\frac{C_P\eta}{\sigma}\approx10^{-2} \quad (41)$$

$$Ra\approx\frac{gl^3\rho^2C_P\Delta P\Delta T}{T\eta\sigma}\approx10^{24} \quad (42)$$

$$Nu=\frac{Ql}{\sigma\Delta T}\approx10^{12} \quad (43)$$

Kolmogorov length is given by: $l\,\mathrm{Re}^{-3/4}\approx10^{-3}cm$. Effect due to tidal stretching (change of area) is quantified by the Karlovitz number, which is given by Equation 44:

$$k_a=\frac{dA}{A}=\frac{A(x_u)-A(x_b)}{A(x_u)}\cong t_f\frac{1}{A}\frac{dA}{dx} \quad (44)$$

where, t_f is the flame thickness Equation 45:

$$V_{F_t}=V_{F_l}{}^o\left(1+\left(\frac{1}{L_e}-1\right)\frac{Ze}{2}\ \mathrm{ka}\right) \quad (45)$$

where, L_e is the Lewis number Equation 46:

$$\mathrm{V_{Fl}=V_{Fl}}{}^0(1+\mathrm{M_a k_a}) \quad (46)$$

Change in the flame speed causes several flame instabilities (Reinecke *et al*., 2002). The Landau-Darrieus instability gives us a mechanism for the accelerating burning rate of detonation in a white dwarf. For a density ratio $r=\frac{\rho_u}{\rho_b}$, the growth rate is given by Equation 47:

$$\exp\left[\frac{rkV_{Fl}^0}{r+1}\left(\frac{r^2+r-1}{r}+kt_fM_a\left(kt_fMa+2\alpha-1+kt_fM_a\right)\right)\right] \quad (47)$$

Consider the reaction $^{12}C+^{12}C$ (Clayton, 1984; Caughlan and Fowler, 1988; Niemeyer *et al*., 1996) Equation (48 and 49):

$$\frac{dX_C}{dt}=-\frac{1}{12}X_C{}^2\rho N_A\lambda \quad (48)$$

$$N^\lambda{}_A=5\times10^{26}\left(\frac{T_{9_1crit}^{\frac{5}{6}}}{T^{\frac{3}{2}}{}_9}\right)\times\exp\left(\frac{-85}{T^{\frac{1}{3}}{}_{9_1crit}}-2.2\times10^{-3}T_9^3\right) \quad (49)$$

where, $T_9=\frac{T}{10^9}$ and X_C is the mass fraction of ^{12}C.

For each ^{24}Mg nucleus created, 13.9MeV is released. The reactions would proceed further as:

$$^{24}Mg(\alpha,\gamma)\ ^{28}Si,...$$
$$^{28}Si + {}^{28}Si \rightarrow Ni^{56}$$
$$^{28}Si + {}^{28}Si \rightarrow Ni^{56}$$

4.2. Possible Formation of Quark Star

The NS can also shrink to a Quark Star (QS) by accretion of impacting white dwarf fragments. Accretion rate of the corresponding fall back material is given by, (Priceand Rosswog, 2006) Equation 50:

$$\dot{m} \approx 10^{29} g/s\left(\frac{\rho_{acc}}{10^7 g/cc}\right)\left(\frac{R}{10km}\right)^{\frac{3}{2}}\left(\frac{M}{1.4M_{sun}}\right)^{\frac{1}{2}} \quad (50)$$

where, ρ_{acc} is the density of accreted matter.

The rotational period of a newly formed NS (or QS) is of the order of 1-2ms. The magnetic field is of the order of 10^{13}-10^{15}. Light cylinder Radius is given by Equation 51:

$$R_L = \frac{c}{\Omega} = 95km\left(\frac{P}{2ms}\right) \quad (51)$$

Magnetospheric radius (R_{mag}) is obtained from the relation, Ram pressure of infalling matter ≅ magnetic field pressure. The slow down due to the magnetic dipole emission causes collapse of NS to BH. During this process jets are emitted along the rotational axes Equation 52:

$$R_{mag} = \left(\frac{B^2R^6}{2\dot{m}(2GM)^{\frac{1}{2}}}\right)^{\frac{2}{7}} = \left(\frac{B}{10^{15}G}\right)^{\frac{4}{7}} \left(\frac{10^{29} g/s}{\dot{m}}\right)^{\frac{2}{7}}\left(\frac{R}{10km}\right)^{\frac{12}{7}}\left(\frac{1.5M_{sun}}{M}\right)^{\frac{1}{7}} 60km \quad (52)$$

The co-rotation radius R_{CO} is Equation 53:

$$R_{CO} = 30km\left(\frac{M}{1.4M_{sun}}\right)^{\frac{1}{3}}\left(\frac{P}{2ms}\right)^{\frac{2}{3}} \quad (53)$$

4.3. Propeller Regime

In falling material may be accelerated and hence carries away angular momentum (10^{30} grams carrying away 10^{50} ergs in ten seconds) (Lattimer and Prakash, 2004) Equation 54:

$$j_{prop} = 10^{47} erg\left(\frac{\dot{m}}{10^{29} g/s}\right)\left(\frac{R_{mag}}{60}\right)^2\left(\frac{2ms}{\rho_0}\right) \approx 10^{52} ergs \quad (54)$$

The rotational energy carried away in jets is of the order of 10^{52} ergs, sufficient to power a short duration GRB. We can classify the various scenarios as arising from the following impact possibilities or impact types in **Table 1**.

There are 28 different possibilities.

Let the masses of the colliding bodies are M_1 and M_2 such that, $M_1 >>> M_2$, with radii, R_1 and R_2. The glancing event problem $\approx \frac{R_2}{R_1}$

The energy is given by Equation 55:

$$E \approx \frac{GM_1M_2}{R_1} \quad (55)$$

And the velocity Equation 56 to 58:

$$v \approx 600km/s\left(\frac{M_{sun}}{R_{sun}}\right)^{\frac{1}{2}} \quad (56)$$
$$c_s \approx 10 - 50km/s$$

The shock crossing time is given by: $\frac{R_2}{c_s} \approx t_s$

$$\frac{dE}{dt} \approx \frac{E}{t_s} \approx 10^{48} erg/\sec\left(\frac{M_{sun}}{r_{sun}}\right)\left(\frac{r_{sun}}{c_s}\right) \quad (57)$$

$$T_{PK} = \left(\frac{\eta L_{Edd}}{4\pi R^2{}_L \sigma}\right)^{\frac{1}{4}} \quad (58)$$

Table 1. Various scenarios arising from different impact possibilities

Impact possibilities	Result
WD hits Red Giant (RSG)	WD + WD
	WD + Disk +WD
	NS or BH + Disk + WD
	RSG → SN
NS hits RG	NS
	NS or BH + Disk+
NS hits RSG	RSG→SN
	NS or BH + Disk + WD
NS hits NS	NS or BH + Disk
NS hits WD	NS or BH + Disk
Canonical→ NS hits NS	NS or BH + Disk
WD hits WD	NS
WD hits MS	WD
MS hits MS (Depending on mass)	WD + WD
	NS + NS
	BH
MS hits RSG	WD + WD
MS hits RG	NS + NS
SG hits SG	
SG hits RG	
RG hits RG	

The mass of material ejected on impact is given by (Sills, 2001; Hurley and Shar, 2002) Equation 59 and 60:

$$\frac{m_{ej}}{m_0} \cong 0.1\left\{\frac{V_{imp}{}^2}{8}\left(\frac{\rho_{tar}}{m_{imp}}\right)^{\frac{1}{3}}\right\}^{0.48} \quad (59)$$

$$\frac{m(>V_{esc})}{m_{imp}} \approx 0.1\left(\frac{\rho_{imp}}{\rho_{tar}}\right)^{0.2}\left(\frac{V}{V_{esc}}\right)^{1.2} \quad (60)$$

The above equations follow from Impact theory (to obtain this the Hertz theory of impact may be used).

5. CONCLUSION

In this study we have looked at the possibilities of nuclear detonation around stellar remnants and its consequences. We have considered the possibility of type Ia supernova being produced by sub-Chandrasekhar and super-Chandrasekhar WD's, rather than only the canonical limiting mass white dwarf. The energetics involved that could make such scenarios plausible agrees with the numerical analysis. We also propose a new model (Smashnova model), where a supernova is followed by a gamma ray burst. The material falling on to the neutron star at relativistic velocities cause its collapse to a magnetar or quark star or black hole leading to a gamma ray burst. Also other variations of possible 'smash-ups' and their dynamics are analysed.

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