PROCEEDINGS OF SCIENCE

Recycling of Neutron Stars in Common Envelopes: A New Mechanism of Hypernovae Explosions.

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In this paper we propose a new plausible mechanism of supernova explosions specific to close binary systems. The starting point is the common envelope phase in the evolution of a binary consisting of a red super giant and a neutron star. As the neutron star spirals towards the center of its companion it spins up via disk accretion. Depending on the specific angular momentum of gas captured by the neutron star via the Bondi-Hoyle mechanism, it may reach millisecond periods either when it is still inside the common envelope or after it has merged with the companion core. The high accretion rate may result in strong differential rotation of the neutron star and generation of the magnetar-strength magnetic field. The magnetar wind can blow away the common envelope if its magnetic field is as strong as 10^{15} G, and can destroy the entire companion if it is as strong as 10^{16} G. The total explosion energy can be comparable to the rotational energy of a millisecond pulsar and reach 10^{52} erg. However, only a small amount of ^{56}Ni is expected to be produced this way. The result is an unusual type-II supernova with very high luminosity during the plateau phase, followed by a sharp drop in brightness and a steep light-curve tail. The remnant is either a solitary magnetar or a close binary involving a Wolf-Rayet star and a magnetar. When this Wolf-Rayet star explodes this will be a third supernovae explosion in the same binary.

25th Texas Symposium on Relativistic Astrophysics - TEXAS 2010
December 06-10, 2010
Heidelberg, Germany

PoS(Texas 2010)085

1. Introduction

The observations of fast rotating NS suggest a presence of a limiting value for the rotation period: the fastest known millisecond radio pulsar has the frequency of 641 Hz [1]; and the rotational frequency of the fastest X-ray pulsar is ~ 760 Hz [2]. It is rather feasible that the gravitational radiation losses posse such a limit. Indeed, as the rotation spin grows the star may enter a regime where its r-mode oscillation is excited via the emission of gravitational waves [3]. The heating of NS, associated with the oscillations, reduces the viscosity and decouples its interior from the outer layers. This may result in a magnetic explosion [4]: the strongly disturbed outer layers rapidly loose their angular momentum via gravitational radiation, this leads to a strong differential rotation and generation of magnetar strength magnetic field in the stellar interior. Eventually, this amplified magnetic field becomes unstable to the buoyancy instability and emerges on the surface, and a powerful magnetically driven pulsar-like wind rapidly extracts the rotational energy of the star. This scenario provides an efficient way to realize the rotation power to the explosion. In particular, [4] proposed this scenario as an alternative interpretation of long GRBs.

2. Inspiral dynamics and recycling of NS

As the neutron spirals inside its giant companion it accretes mass and angular momentum. The accretion can proceed at the Eddington rate or at the much higher Bondi-Hoyle rate if the radiation generated during the collision of accreted matter with NS or its accretion disk becomes trapped in the accretion flow. This depends on the position of the accretion shock, which depends of the efficiency of neutrino cooling [5, 6, 7]. Only if the accretion proceeds at the Bondi-Hoyle rate the recycling of NS is sufficiently fast and the explosion can occure.

The Bondi-Hoyle mass accretion rate is well approximated by the equation

$$\dot{M}_{\text{B-H}} = \pi R_{\text{A}}^2 \rho_\infty v_\infty, \tag{2.1}$$

where R_A accretion radius

$$R_{\text{A}} \approx 2\beta \frac{aM}{M_*}, \tag{2.2}$$

where $\beta \simeq 0.8$ and only weakly depends on model of RSG.

We will assume that

$$\langle j_{\text{A}} \rangle = \frac{\eta}{4} \Omega R_{\text{A}}^2, \tag{2.3}$$

where η is a free parameter, which reflects our current ignorance.

Given the specific angular momentum we can estimate at what radius from NS the Bondi-Hoyle trapped gas will form an accretion disk,

$$R_{\text{c}} = \frac{\langle j_{\text{A}} \rangle^2}{GM} \approx a\eta^2\beta^4 \left(\frac{M}{M_*}\right)^3. \tag{2.4}$$

For $R \gg R_c$ the accretion on NS may proceed in more or less spherical fasion as in the Bondi solution, where at $R_{\text{acc}} = 0.25R_{\text{A}}$, for the polytropic index $\gamma = 4/3$, the accretion flow becomes supersonic. Its collision with the NS surface or the surface of its accretion disk creates a shock wave, which may not effect the mass accretion rate provided two conditions are satisfied.

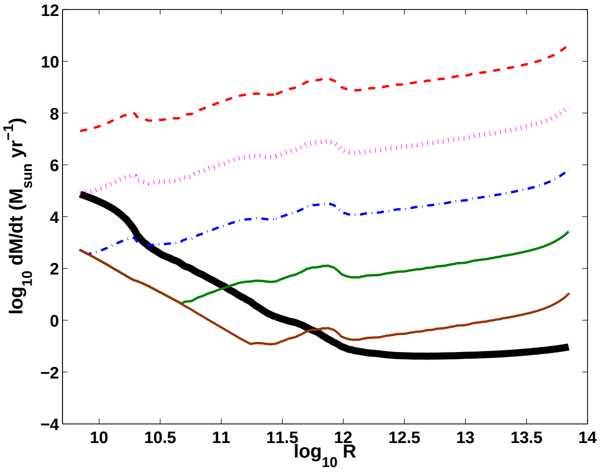

Figure 1: Accretion rate as a function of the distance between the RSG center and NS (we note that NS is accommodated by the RSG star) as obtained in the frameworks of the model suggested by [8] for $M_{\rm rsg} = 25 M_\odot$. The critical accretion rates for the following values of the η parameter are shown: $\eta = 1, 1/2, 1/4, 1/8$ and $1/16$. For these values, the interaction of the NS with the envelop prevents an efficient accretion to the NS, unless the Bondi-Hoyle rate, which is shown by the thick solid line, exceeds the critical value. For the higher accretion rates, the accretion occurs at the Bondi-Hoyle regime.

Firstly, the radiation produced by the gas heated at the accretion shock should not be able to escape beyond $R_{\rm A}$. If it does the radiation pressure prevents the mass accretion rate to exceed the Edington rate. For this to occure $\dot{M}_{\rm B\text{-}H}$ has to exceed the critical value

$$\dot{M}_{\rm cn1} \approx 1.1 \times 10^{-3} \left(\frac{R_{\rm c}}{10^6\,{\rm cm}} \right)^{1.08} M_\odot \ {\rm yr}^{-1} \tag{2.5}$$

Secondly, the shock has to be inside the sonic surface of the Bondi flow. Otherwise, the shock cannot be a part of the stationary solution and hence the Bondi-type accretion is not realised. This condition is satisfied when the $\dot{M}_{\rm BH}$ exceeds the critical value

$$\dot{M}_{\rm cn2} \approx 10^4 \left(\frac{R_{\rm acc}}{10^8\,{\rm cm}} \right)^{-2.7} \left(\frac{R_{\rm c}}{10^6\,{\rm cm}} \right)^{4} M_\odot\,{\rm yr}^{-1}. \tag{2.6}$$

As we shall see this condition is more restrictive. The critical rates are quite sensitive to the parameter η,

$$\dot{M}_{\rm cn1} \propto \eta^{2.16} \quad \text{and} \quad \dot{M}_{\rm cn2} \propto \eta^{8}.$$

Since $M_{\rm cn2}$ is very sensitive to η, Figure 1 shows $M_{\rm cn2}$ few intermediate values of η for the model RSG25. One can see the fast accretion regime (at Bondi-Hoyle rates) is only possible when $\eta \lesssim 1/4$.

Once the accretion disk is formed the specific angular momentum of the gas settling on the NS surface is that of the last Keplerian orbit. In this case the star will reach the rotational rate Ω after accumulating

$$\Delta M \simeq \frac{\Omega I}{j_{\rm K}} \simeq 0.27 \left(\frac{M}{1.5 M_\odot} \right) \left(\frac{R}{10\,{\rm km}} \right)^2 \left(\frac{P}{1\,{\rm ms}} \right) M_\odot \tag{2.7}$$

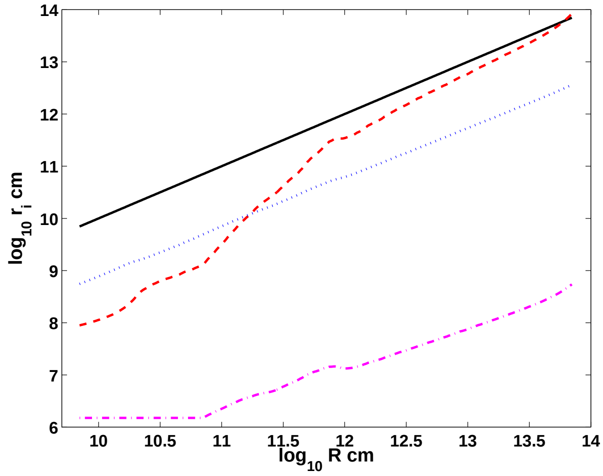

Figure 2: The illustration to the typical linear scales of the scenario as function of the distance between the RSG center and NS. The calculations are performed in the frameworks of the same model as in Fig. 1 for a specific value of the η parameter $\eta = 0.1$. The orbital radius is shown by the solid line, the sonic point, $R_{\rm acc}$, by the dotted line, the accretion shock radius by the dashed line, and the circularization radius, $R_{\rm c}$ by the dash-doted line.

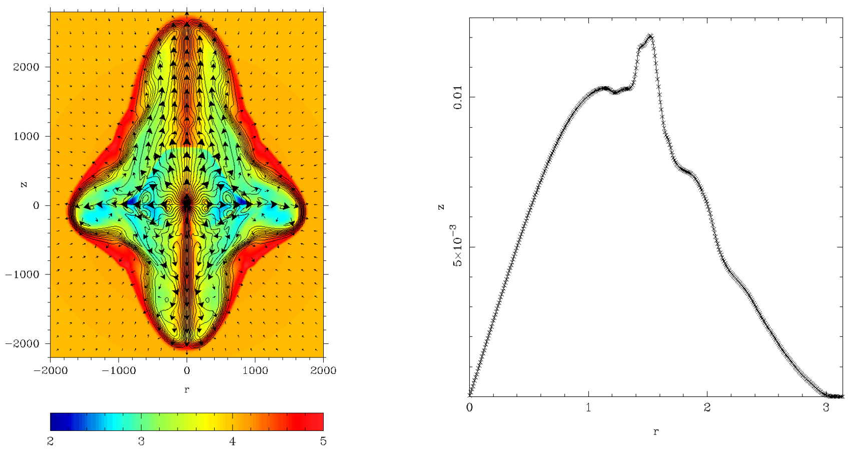

Figure 3: The distribution of the density (left panel) and the angular dependence of the energy flux at the distance of 110 km (right panel) are shown for the moment 0.056 s after the magnetically driven explosion. The initial density was uniform, and the magnetic field was assumed to be a shifted dipole field $B = 3\times10^{15}$ G (see the contour lines in the left panel). The velocity map is shown by arrows in the left panel. It may be seen that the expected released energy flux is strongly anisotropic.

3. Discussion

Our model suggest an interpretation of anomalously bright SN2006gy [9] which is an alternative to the pulsation pair instability supernovae [10]. In a close binary system formed by a normal star and NS, the normal star in the stage of Roche lobe overflow, produces a strong wind from 1^{th} Lagrangian point. When the NS approaches too close, the CE stage has to begin. At this epoch we can expect a very dense stellar wind with mass loss rate at the level of $\sim 1 M_{\odot}\mathrm{yr}^{-1}$. During the CE stage the fast accretion to NS leads to a recycling of the NS up to ms periods. This rotation can overtake the stability limit and GW radiation can start to be very efficient. Thus, the outer layers of NS slowdown its rotation and a strong magnetic field could be generated in the vicinity of NS [4]. In this way, an ideal configuration for the explanation of anomalously bright SN is formed. In the frameworks of our scenario [11], we can explain the big amount of hydrogen in the external envelop and anomaly intensive stellar wind.

One of the important details in this model is that the explosion occurs strongly non-central, when NS is recycled till the limiting frequencies before reaching the center of RSG star. The pressure in the center of RSG is order of 10^{19} erg cm^{-3} and can reach 10^{27} erg cm^{-3} at pre-supernovae stage, thus the pressure in the bubble could be estimated as

$$P_{bub} \approx \frac{3Lt}{4\pi R^3} \approx 8 \times 10^{17} L_{48} v_{sh,-1}^{-1} R_{10}^{-2} \tag{3.1}$$

for the following epoch $t \approx R/v_{sh}$, here R is distance between NS and center of RSG, v_{sh} the shock wave speed in the speed of light units c. We can see that the pressure in the bubble is smaller than the pressure in the center of RSG, unless the explosion occurs at the distance of $R_{10} > 1$, when the shock wave cannot destroy the stellar C/O core. If the explosion occurs in the stellar center vicinity, the whole RSG can be destroyed by the explosion.

In the case of the remote explosion, although the mass of the RSG envelop can be bigger than mass of C/O core and M_{NS}, the binary system cannot be destroyed, since the outer envelop does not influence gravitationally on bounded system of NS + C/O core.

We note that the magnetic field topology is very important. Since the dynamo mechanism can generate multiples configurations, a superposition of dipole and quadrupole magnetic field is expected to produce a shifted dipole field configuration. The shifted dipole model has important features since it should automatically lead to an unsymmetrical explosion and one side energy realize (another examples of one side jets one can find in the works [12, 13]). A detailed numerical simulations display two side jet configurations but with significantly different power in jets (the energy ratio is close to 2:1 –see Fig.3–). This allows to estimate the kick for NS as

$$v_{kick} \leq \frac{E_{tot}}{3M_{NS}c} \approx 370 E_{tot,52}\ km\ s^{-1} \tag{3.2}$$

here $E_{tot,52} = E_{tot}/10^{52}$ ergs.

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