EXPLOSIONS OF VERY MASSIVE STARS AND THE ROLE OF HYDRODYNAMICAL INSTABILITIES

A.A. BARANOV, P. CHARDONNET and A.A. FILINA
LAPTh, Univ. de Savoie, CNRS, B.P. 110, Annecy-le-Vieux F-74941, France

V.M. CHECHETKIN and M.V. POPOV
Keldysh Institute of Applied Mathematics, RAS, Miusskaya sq. 4, 125047, Moscow, Russia

Modern theoretical models predict that massive stars with masses within the 100–250 $M_\odot$ range can produce pair-instability supernovae (PISNe). Since the first stars of the Universe are believed to be very massive, these supernovae should play a significant role in the early stages of its history. But these stars represent the last unobserved population, owing to detection limits of current telescopes. We present an analysis of pair-instability supernovae explosions using various numerical codes. We discuss a possible connection of PISNe with gamma-ray bursts (GRBs) and explanation of some properties of GRB in this framework.

1 Introduction

The first generation of stars in the Universe, so called Population III stars (Pop III), was formed hundreds of millions of years after the Big Bang. Today we do not have direct observations of how the primordial stars were formed. But certainly, the new generation of instruments will give us an opportunity to test theoretical ideas about the formation of the first stars.

Among these first–generation stars, an important role was played by massive stars. As shown by many numerical simulations,[1,2,3] these very massive stars could end their life either by producing pair-instability supernovae (PISNe), leaving no remnant, or by collapse to a black hole. In the case of PISNe, the energy release is tremendous and could possibly be seen with new telescopes (James Webb Space Telescope, European Extremely Large Telescope).

Gamma-Ray Bursts (GRBs) are very high energetic flashes of gamma emission that last for a few seconds and come from cosmological distances. Although they are already known from 1960s and several models of this phenomenon were proposed, [4,5] but until now there is no definite answer on the question “Which objects are the sources of GRBs?”. Recently a new interpretation of GRBs as pair-instability supernovae explosions was proposed by Chardonnet et al. [6]

In this work we present an analysis of the PISN explosion. We present the results of one-dimensional simulations and analysis of the fate of a star depending on physical conditions. We also present 2D simulations of PISN explosion based on the idea of non-uniform explosion. We discuss possible explanation of some features of GRBs in the case if they can be produced by PISNe.

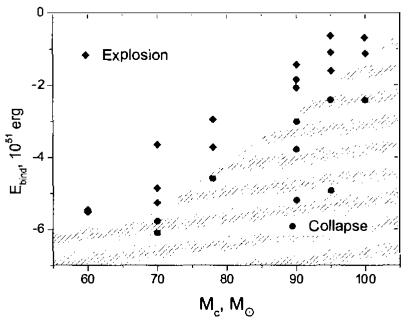

Figure 1: Fate of a star depending on its mass, M_c, and binding energy, E_{bind}. Explosion is marked by diamonds and collapse is marked by circles.

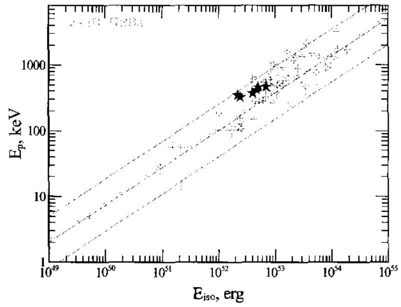

Figure 2: Comparison of the maximum temperature, T_{max}, and total nuclear energy release, E_{nuc}, (shown with stars) with the peak energy, E_p, and isotropic equivalent energy, E_{iso}, of Swift GRBs.

2 Numerical approach

To investigate the behavior of pair-unstable stars, we performed various hydrodynamical simulations. With the one-dimensional (1D) Lagrangian code, we studied the fate of oxygen cores depending on mass and initial configuration. To study the last stage of explosion when shock-wave propagates outward, we applied a two-dimensional (2D) code. There are a few recent modelizations of PISNe in 2D. [7,8] In both cases a modern astrophysical code, CASTRO, has been used. To investigate the influence of hydrodynamical solvers we applied our own numerical code based on the Piecewise Parabolic Method on a Local stencil (PPML). [9,10]

2.1 Modelization in 1D

We performed the hydrodynamical simulations for the several models of stars with different masses of the core M_c. We considered only the cores, initial composition was assumed to be pure oxygen. Initial configurations were computed from the hydrostatic equilibrium condition with the polytropic index $\gamma = 4/3$. For each core having mass M_c, we built several configurations by choosing different values of central density, ρ_c. This allowed us to consider models with different values of binding energy, E_{bind}. Thermodynamical quantities at the center that we chose and values of binding energy are very close to the results of evolutionary calculations. [3]

For the 1D computations we developed a numerical code based on the standard Lagrangian approach. [11] The equation of state that we used takes into account the birth of electron–positron pairs. [12] Energy release from nuclear burning and neutrino losses were taken into account. Nuclear burning was followed by α-chain of reactions up to ^{56}Ni.

An important fact was established that the fate of the core depends on the value of initial binding energy E_{bind}. The critical value of E_{bind} depends on the mass of the core M_c. Two regions could be seen clearly on M_c–E_{bind} diagram (Fig. 1). This behavior could be explained by the fact that models with lower E_{bind} (higher absolute value of E_{bind}) gain higher kinetic energy to the moment of oxygen ignition and proceeds faster to Fe-He transition zone (photodissociation). Thus outer layers of the core have not enough time to bounce and expand. Therefore the pressure on the central part couldn't be reduced. Photodissociation dramatically drops down the pressure in the center and the core collapses. The critical value of E_{bind} tends to zero with growth of M_c. Taking into account that for a stable non-rotating configuration the binding energy should be negative, we can propose the mass limit for the explosion of non-rotating oxygen core at value about 110 $M_\odot$. This value is in a good agreement with results of the previous works. [13,14]

An interesting correlation has been found for the models that explode: value of total nuclear

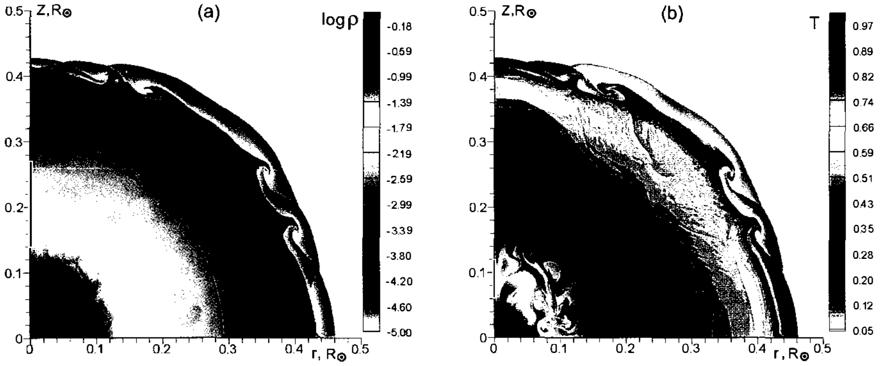

Figure 3: SN model with multi-core ignition for the moment $t = 28$ sec. Logarithm of density (a) is shown in the units of $\rho_c = 2.65 \times 10^5$ g/cm^3. Temperature (b) is shown in the units of $T_c = 2.36 \times 10^9$ K.

energy release, E_{nuc}, increases with maximum temperature T_{max} at the center (Fig. 2). If we consider PISN as a source of GRB then in the case of the total disruption of a star hot matter of the core could be ejected outside. Energy gathered from nuclear burning will be emitted by electromagnetic radiation with the same characteristic energies as the temperature of the matter. The efficiency of the transformation of the nuclear energy into the emission should be high, since therc are no intermediate processes of transformation and redistribution of energy. Assuming that the progenitor of GRB is a pair-instability explosion of a very massive star, it is natural to associate the peak energy E_p with the maximum temperature, T_{max}, and the total isotropic energy, E_{iso}, with the nuclear energy release E_{nuc}. It is seen from Fig. 2 that computed values and observational data of GRBs [15] are in a good agreement.

2.2 Numerical explosion in multi-D

To study the role of hydrodynamical instabilities on the process of explosion we performed 2D computations. Hydrodynamic simulations were performed with numerical code based on the Piecewise Parabolic Method on a Local stencil (PPML). [9,10]

We chose simplified physical model of explosion, neglecting the energy release from nuclear reactions and gravity changes. The main goal was to obtain the principal possibility of the total disruption of the stellar core to many fragments in the case of very massive progenitor. We investigated a Pop III star with 100 $M_\odot$ oxygen core assuming rotational symmetry. As in 1D case we used polytropic model of a star with index $\gamma = 4/3$.

The explosion was simulated by deposition of thermal energy in central region. The energy was inserted by the series of 10 ignition bubbles at the moment of $t = 0$ sec. All of the bubbles had different energy values and sizes distributed in a stochastic way. The total energy deposited was $E = 5 \times 10^{52}$ ergs. This nonuniformity could present some inhomogeneities in the core that occur prior to explosion. Nuclear burning in the center of a star could cause the development of large-scale convection. [16] If convection occurs prior to the moment of pair-instability, the contraction and explosion could be non-symmetrical. Inhomogeneities in temperature and density could lead to the occurrence of ignition spots in the core.

The results of the computations are presented in Fig. 3. It shows the density and the temperature for the moment $t = 28$ sec. The shock, produced by the explosion, is split on 2 fronts propagating through the rarefied matter and heating it. In the central part of the core there is a region with Rayleigh-Taylor instability. The radius at which this instability occurs is very close to the value obtained by Chen et al. [7] Many spots of hot matter appears behind the shockwave. This could lead to the disruption of the star in many fragments. As a result the light curves of such supernova could be very complex, which could be a possible explanation of time-variability of GRBs.

3 Discussions and conclusions

We presented our analysis of PISN explosion. Results of 1D simulations are in a good agreement with previous works. We proposed the initial binding energy of a star as the criteria of its subsequent fate. An interesting correlation between total nuclear energy release and maximum temperature has been found which could be a key to understanding the Amati correlation.

We performed also the 2D numerical simulations. We proposed multi-core ignition scenario to explore non-uniform PISN explosion. This could be an "exotic scenario", but if the explosion is non-uniform it could change the light curve, chemical production and also the spectrum.

Another key question of PISN explosion phenomena is the role of envelope. In order to explain properly GRB with PISN the envelope of a pre-supernova must be removed in a certain way. Woosley et al. [17] proposed the idea that quite small pulsation of pair-unstable star could eject the envelop. Non-uniform explosion of a star without envelope could produce light curve that is different from typical plateau-type, having very complex behavior, typical for GRBs.

Acknowledgments

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