Challenges of a theory of supernova explosions (extended abstract)

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1 Introduction

A supernova explosion is a second worst thing that can happen to a star[1]. When a supernova explodes, about $\sim 10^{51}$ or more ergs of energy is released in the outer space in a form of kinetic energy of matter and as a radiation. A supernova becomes as bright, with luminosity of $\sim 10^{43}$ ergs/s, as the entire galaxy in which it occurs.

Observationally, supernovae can be divided on two types, Type I and Type II, according to absence or presence of hydrogen in the ejected material, respectively. Type I is further subdivided on Type Ia, Ib, and Ic supernovae, depending on whether silicon (Si) is present (Ia) or absent (Ib,c) in their spectra, and on certain other details. There are subdivisions in Type II class as well.

A physical mechanism of a supernova explosion is either a gravitational collapse of a stellar core or a thermonuclear explosion. Type Ia supernovae are thermonuclear explosions of degenerate stars – carbon-oxygen white dwarfs. All other types, Type II and Type Ib,c, are believed to be core-collapse supernovae.

2 Type Ia (thermonuclear) supernovae

Let us first talk about thermonuclear supernovae. A degenerate matter of a carbon-oxygen white dwarf consists of fully ionized nuclei of C and O, and of degenerate electrons. The latter provide pressure that helps a white dwarf to withstand gravitational contraction and keep it in a hydrostatic equilibrium. Degenerate pressure depends on density of matter but is virtually insensitive to variations of temperature. Normal (non-degenerate) stars like the Sun are thermally stable and do not explode because their pressure is temperature-dependent and reactions can be stabilized by work against gravity. But in degenerate stars thermonuclear reactions can accelerate exponentially[2]. It is believed that a thermal blowup ("thermonuclear runaway") takes place and a Type Ia explosion begins when a degenerate star captures mass

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[1]An absolute worst is, of course, to be swallowed whole by a black hole, and disappear from this world completely and without notice.

[2]reactions can be temporally kept in check by energy losses due to radiation of neutrino and by heat conduction

from a stellar companion in a binary stellar system, and its mass grows and approaches a so called Chandrasekhar limit $M_{CH} \simeq 2.8 \times 10^{33}$ gram.

Type Ia supernovae are very important tools for determining fundamental properties of the universe. Their use as distance indicators has lead to accurate measurements of the Hubble constant, and to a recent discovery of accelerating expansion and the presence of a mysterious dark energy in the universe. The main idea behind the latter was to observe how brightness of SNIa depends on expansion velocity of a host galaxy. General relativity predicts that this relation depends on a cosmological model and is controlled by such fundamental parameters as the average matter density, Ω_M and dark energy density, ω_Λ, of the universe. By comparing theory with observations of supernovae, one can determine the difference $\omega_\Lambda - \Omega_M$. Additional observations of microwave background anisotropy can be used to determine $\omega_\Lambda + \Omega_M$. By combining the two types of observations, one can determine ω_Λ and Ω_M separately. A non-zero Ω_Λ found in observations indicates a presence of dark energy. Critical to all this is the underlying assumption that Type Ia supernova are "standard candles" - that they all have the same intrinsic brightness regardless of where and when they explode.

The problem is that Type Ia supernovae are not standard candles. Their intrinsic brightness could change from one event to another by a factor of a few. However, there is an empirical correlation between maximum brightness and the rate with which brightness of supernova declines with time. This can be used to factor brightness variations out. Unfortunately, the brightness-decline relation is only approximate, and deviations of individual supernovae from the average behavior are the main source of uncertainty in determining cosmological parameters. It is critically important to understand a Type Ia explosion mechanism, the brightness-decline relation, and the causes underlying the diversity of these supernovae.

Figure 1 shows results of a three-dimensional simulation of a Type Ia supernova. It has been carried out starting from a Chandrasekhar-mass hydrostatic white dwarf and including the exact equation of state of degenerate matter, an appropriate nuclear reaction network, forces of gravity. Important underlying assumption are: (1) an explosion starts at the center of a star as a laminar flame and not as a detonation. Speed of a laminar flame in a supernova can be calculated very accurately. As the flame moves away from the center, gravity increases, and the flame becomes Rayleigh-Taylor unstable an turbulent. It is assumed (2) that on numerically unresolved scales the flame is in a self-similar regime and that its effective speed can be described by a sub-grid model $S_t \simeq \alpha\sqrt{g\Delta}$ where $\alpha \sim 1$ is a free parameter, g is a local acceleration of gravity, and Δ is a cell size. (3) turbulent deflagration takes place without transition to a detonation (no DDT).

The main result of this and subsequent simulations [1,2] is that deflagration explosion releases enough energy to produce a supernova explosion. However, results are not exactly what is observed. The model predicts almost total overturn of burned and unburned matter with iron group elements, silicon group elements and unburned carbon-oxygen mixed through the entire star. This seems to contradict observations which indicate a rather layered structure with partially burned matter in the outer layers of a supernova, and completely burned material moving behind. We need to critically explore main underlying assumptions of the model to see what should be changed to get better consistency with observations.

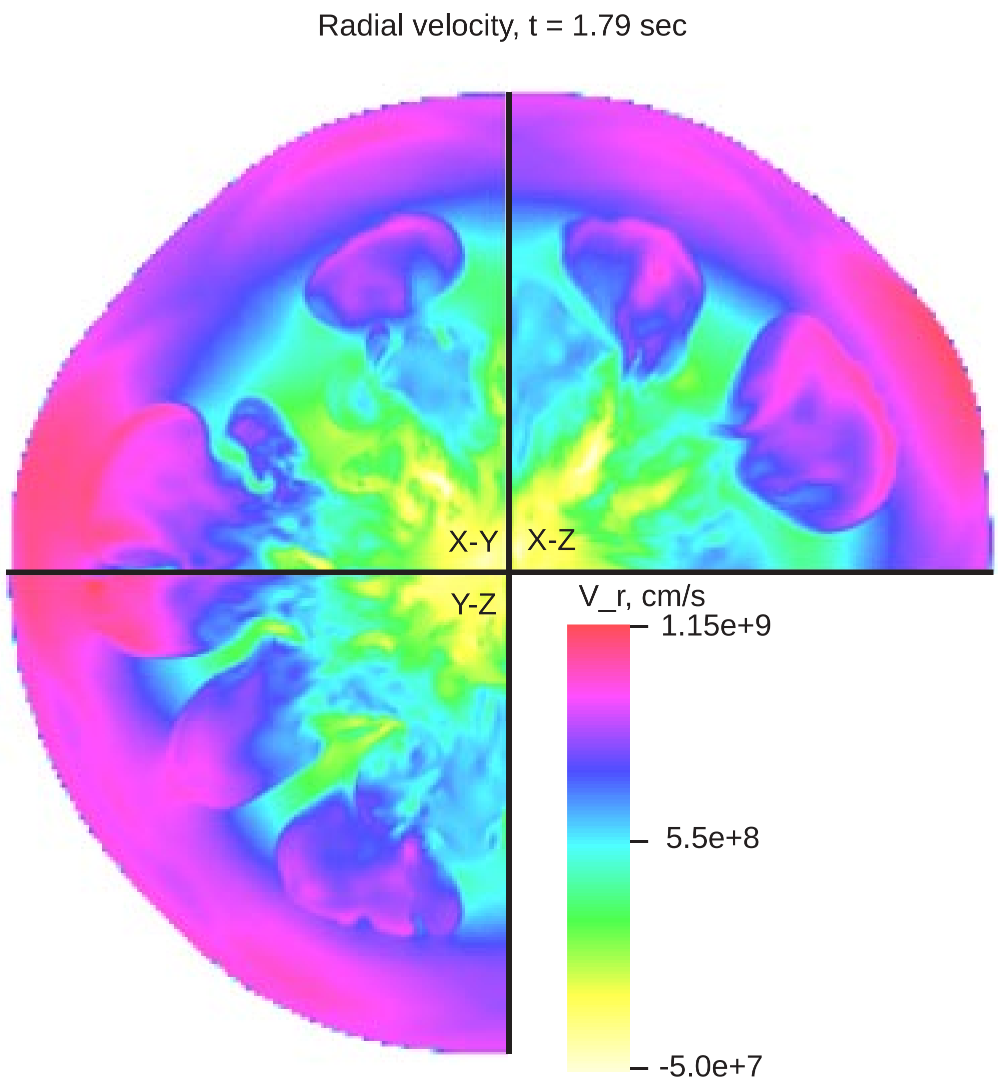

Figure 1: A deflagration explosion of a supernova [1]. Shown is a radial velocity field in three orthogonal planes 1.8 s after ignition. The explosion is well underway and the star is expanding supersonically. Seen are blobs of burned matter rising in gravitational field as well as unburned material sinking towards the center.

(1) *Ignition.* Observations tell us that explosion must start as a subsonic deflagration. Otherwise the star cannot expand while it burns, and silicon, so prominently seen in Type Ia spectra, cannot be produced. However, we do not know how exactly the flame is started: in just one or in many spots. Some convection motions must be generated by the accelerating nuclear reactions even before flame is ignited. How strong are they? Do they play a role in cooling off the reactions? Can they delay the ignition? Can a significant portions of matter be burned before a flame front appears? How would it affect the subsequent explosion?

(2) *Sub-grid turbulent burning model.* What happens in intermediate regimes of low gravity where flame is being influence by the Rayleigh-taylor instability but the level of turbulence is not yet strong enough to completely dominate the flame propagation, and the flame is not in a self-similar regime?

(3). *Deflagration-to-detonation transition.* It has been suggested that transition to detonation happens in Type Ia supernovae. This helps with a number of problems occurring in pure deflagration models. In particular, detonation is expected to completely burn carbon-oxygen fuel and partially burned matter in central parts of the star, and to make the explosion more spherically symmetric. Detonation also is expected to incinerate unburned outer layers not affected by the deflagration. Resent three-dimensional simulations with artificially triggering DDT in a Type ia supernova after a brief period of deflagration confirm these ideas and help improve the explosion model. The question is how exactly DDT could happen in a supernova? Can we predict when it should happen from first principles?

3 Core-collapse supernovae

Recent observations of core collapse supernovae provide increasing evidence that the explosion is intrinsically asymmetric: (1) Spectra of core-collapse supernovae are significantly polarized indicating highly asymmetric envelopes. The degree of polarization tends to vary inversely with the mass of the hydrogen envelope, being maximal for supernovae with no hydrogen (Ib and Ic events). The degree of polarization also tends to increase with time as we can see deeper layers of the ejected matter closer to the center. (2) Neutron stars born in the process of a core collapse are observed with high "kick" velocities up to 1000 km/s. (3) Remnants of some of supernovae attributed to core collapse show an unusual asymmetric stratification of chemical elements. (4) Early observations of a supernova SN1987A showed that radioactive material was brought to the hydrogen rich layers very quickly during the explosion. Spectra-polarization observations of SN1987A showed deviations from spherical symmetry; and speckle observations indicated deviations from spherical symmetry as well. (5) Fifteen years after the explosion of SN1987A, the Hubble space telescope resolved rapidly expanding inner layers of the ejected matter of this supernova. The late time images and spectroscopy clearly show a highly structured, axially-symmetrically ejected material with fast moving iron and slower moving oxygen and silicon which is consistent with early observations. Most recently, an intimate observational link has been discovered between γ-ray sources (highly collimated and enormously powerful bursts of energy) and Type Ib,c supernovae. All this makes a case for an intrinsically strongly asymmetric explosion mechanism operating in many if not all core collapse supernovae, and leads to considering jet-induced supernova models. Jets can presumably be created by a combination of rotation, magnetic fields, and/or generation of direct electro-magnetic radiation during core collapse.

Figure 2 shows an example of a calculation of such an explosion driven by a high density non-relativistic jets emanating from a neutron star newly formed in the process of a core collapse. A highly asymmetric explosion mechanism can explain many of the observations discussed above.

4 Experimental modeling of supernova phenomena

A number of experiments may be useful for understanding supernova physics:

- Experiments directed at understanding DDT are critical, in particular investigation of DDT in unconfined conditions, in large volumes, and at level of turbulence expected to take place in supernova conditions.
- A (possibly statistical) theory of thermonuclear runaway is required. Can experiments on mild ignition behind reflected shocks (similar, for example to these recently carried out by Geraint Thomas and collaborators) shed some light on this process? Can the interplay of ignition and convection be studied at different (gravity) acceleration in a drop tower or a centrifuge?
- Measurements of turbulent velocity and reaction fields in turbulent combustion in a gravitational field, and the dependence of turbulent burning on gravity can be important for developing and calibrating sub-grid model for turbulent burning in supernovae.
- Generation of supersonic jets by means of explosions, and studying interaction of supersonic jets with ambient material may be important for modeling jet-induced explosions of core collapse supernovae.

A possibility of these and other types of experiments, as well as a number of directions where combustion and explosion theory can be applied to supernovae opens an exciting inter-disciplinary field of research.

References

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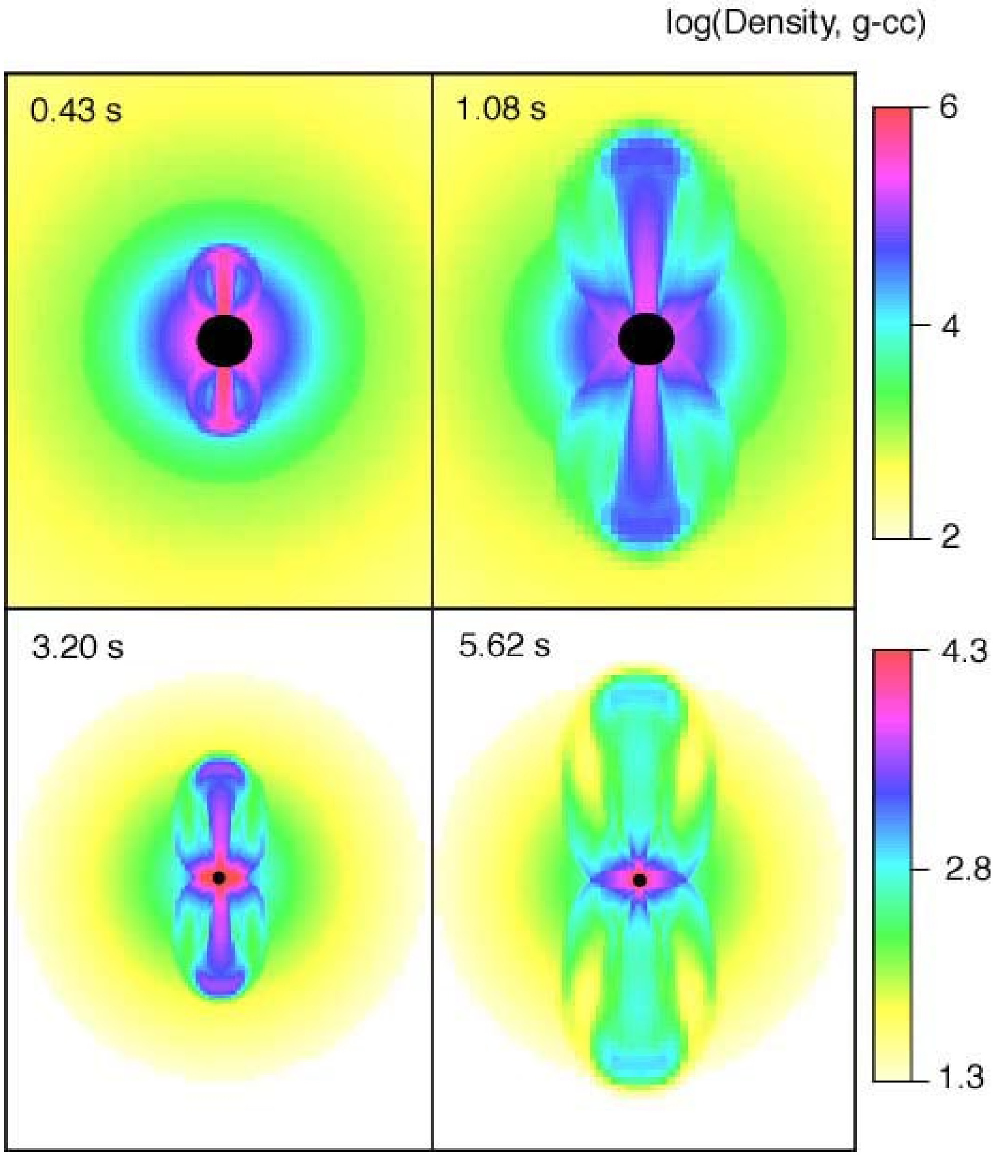

Figure 2: A jet induced explosion of a massive helium star (a Type Ib supernova) [3]. Oppositely directed jets of material emanate from a newly born neutron star and propagate through a stellar envelope. A highly asymmetric bow shocks eventually cause an ejection of an asymmetric ejection of matter. Last frame shows a jet breaking through a stellar surface. After that, the jet will freely propagate through a very low density circumstellar medium.