The SuperNova Explosion How and When

The short history of stars:

$M<0.08M_{sun}$ Too low central temperature to ignite H

$0.08<M<0.8$ MS life time $\sim 10^{10}(M/M_{sun})^{-4}$years > Universe age

$0.8<M<10$ Ejects a planetary nebula and ends as a WD

$10<M<60$ The standard SN model

$60<M$ Does not stay on the MS?

A SN which does not leave a neutron star and goes directly to BH

The condition for stellar stability

Consider a simple polytropic equation of state: $P=K\rho^n$

**A polytropic e.o.s. is a generalization of adiabatic process.
In adiabatic process $n=\gamma$. In a general process $n=c/c_v$.**

We assume therefore that the star behaves like a certain heat machine.

Suppose we slightly contract the star: $\delta\xi = -\frac{\delta R}{R}$

The mass is constant and hence:

$$\delta(\rho R^3) = 0 = \delta(\ln\rho + 3\ln R)$$

So: $\frac{\delta\rho}{\rho} = 3\delta\xi$ **and** $\frac{\delta P}{P} = \gamma\frac{\delta\rho}{\rho} = 3\gamma\delta\xi$

On the other hand: from hydrostatics: $\frac{dP}{dR} = -\frac{GM\rho}{R^2}$

Consider for simplification average values, than: $\langle P\rangle \sim \frac{\rho}{R}$

This <P> is essentially Pgrav : the gravity pressure

Hence $\frac{\delta Pgrav}{P} \sim \frac{\delta\rho}{\rho} - \frac{\delta R}{R} = 4\delta\xi$

For stability of the star:

Upon contraction: gas pressure must increase more than the gravitational pressure. This means:

Increase of gas pressure $\quad 3\gamma\delta\xi > 4\delta\xi \quad$ Increase of gravitational pressure

The condition for stellar hydrostatic stability

$$\gamma > 4/3$$

For a gas we have for const. volume: $\quad \Delta Q = C_V \Delta T$

For ideal gas $\quad \gamma = \frac{C_P}{C_V} = \frac{C_V + R_{gas}}{C_V}$

What affects the adiabatic exponent γ?

Consider a process in which heat enters the system but the temperature does not rise.
Example: the heat goes into ionization, breaking nuclei etc

If heat is pumped into the system and T does not rise it means that C_v is very large.

In this case: $\quad \gamma \to 1$

As soon as γ goes below 4/3 an instability appears and the equality of pressures creating the hydrostatic equilibrium is broken:

The consequence is a collapse of the star.

Examples: collapse of a gas cloud to form a star when T increases To ionize the hydrogen

Possible stellar disasters during the evolution

Fe photo-disintegration at

$$T \quad 7\times 10^9 K \quad \rho \approx 10^7 gm/cc$$

$$Fe^{56} + \gamma \to 13He^4 + 4n - 2.1\times 10^{18} erg/gm$$

This process is followed with the breaking of He nuclei

$$He^4 + \gamma \to 2p + 2n - 6.8\times 10^{18} erg/gm$$

The energy of the photon, the γ, is spent in the binding energy of the nuclei and NOT is the pressure. The pressure drops in about 10^{-6}sec (the dynamical time scale) leading to a *fast core collapse*

Pair formation

$$2\gamma \rightarrow e^{+} + e^{-} - 2m_e c^2$$

The strong radiation field in massive stars creates out of the vacuum pairs of electron-positron .

The photon energy is invested in the rest mass of the newly created pair and the kinetic energy of the pair.

The pair creation leads to lowering of γ and a collapse

Detonation of nuclear fuel

Usually the rate of nuclear energy production is very T sensitive.
So a rise in energy production leads to a large rise in P, expansion of the burning volume and decrease in P.
This situation is stable. There is a negative feedback.

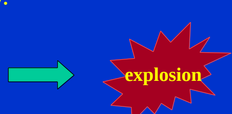
The condition for stability of nuclear burning is High T sensitivity

When C and O burn in degenerate matter the gas pressure depends essentially only on the density

$$P \quad \begin{cases} \rho^{5/3} & \text{non relativistic} \\ \rho^{4/3} & \text{relativistic} \end{cases}$$

The pressure does not depend on the temperature in a cold degenerate gas.

As the reactions start, they heat the core and T rises without increasing the gas pressure. A huge amount of heat is pumped into the gas before degeneracy is lifted. When it is lifted, the gas contains a large amount of energy and expands quickly against gravity.



Instabilities from violating the Chandrasekhar critical mass

The limiting mass for a cold dense low mass star is

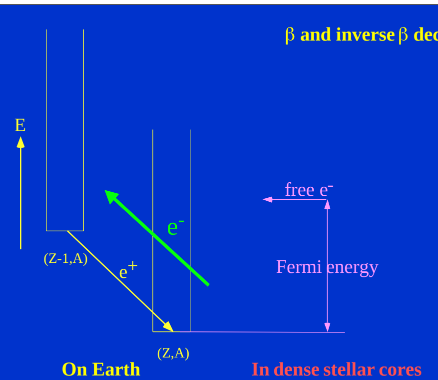
$$M_{ch} = 5.76\left(\frac{Z}{A}\right)^2 M_{sun}$$

Two process can change the limiting mass of a star
A) Inverse β decay under the high density in the core

$$(Z,A) + e^- \rightarrow (Z-1,A) + \nu$$

An electron from the continuum is absorbed by the nucleous (Z,A). In the lab (Z,A) is the daughter of (Z-1,A) which decays into (Z,A) by emitting a positron.

β and inverse β decays



A White dwarf in a binary system may accrete mass from its neighbor and increase its mass continuously.
The process continues until the mass of the WD violates the Chandrasekhar limiting mass.

A fast collapse follows which leads to SN and a neutron star and may be even a Black Hole.

SuperNova

The most energetic explosion in the entire universe.
The entire stellar envelope in blown away at a speed of 10,000-30,000km/sec
The total energy release is 10^{53}ergs over a period of less than a year.
A SN is brighter than a galaxy!

The dynamic time is given by:

$$\tau_{dyn} = \frac{1}{\sqrt{\frac{4\pi}{3}G\rho}} \sim \frac{1000}{\sqrt{\rho(cgs)}}\sec$$

τ_{dyn}(core) ~ 1/3 ms

τ_{dyn}(envelop) ~ 10sec

When the core collapses the envelope does not move!

The collapse creates conditions under which many ν are formed

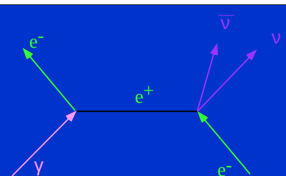
Neutrino creating processes

- Inverse β decays due to high density
- $e^+ + e^- \rightarrow \nu + \bar{\nu}$ Occurs at about $T \sim 10^9 K$
- $plasmon \rightarrow \nu + \bar{\nu}$

  At high density the natural frequency of the plasma reaches values such that: $\hbar\omega_{plasma} \approx kT$

- $\gamma + e \rightarrow e' + \nu + \bar{\nu}$

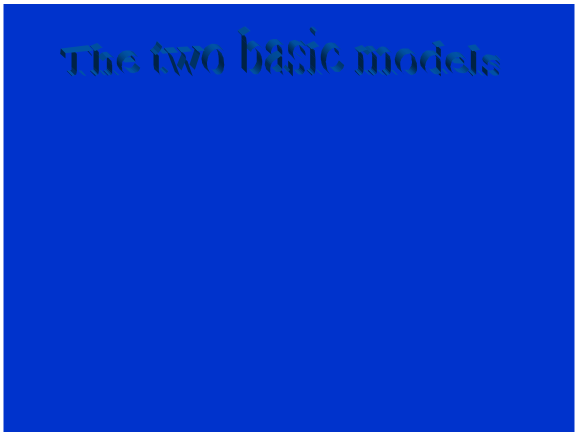
  Like Compton scattering but instead of γ, ν are emitted



- Bremsstrahlung $e + Z \rightarrow e + Z + \bar{\nu} + \nu$

Copious amounts of neutrinos are emitted during the SN collapse. Some of these neutrinos were observed in underground neutrino Experiments when the most recent closest SN (in the Magellanic Clouds) took place in 1987.


Shock Waves


The two basic models

Problems with SN models

Shock ejection:

Extreme sensitivity to e.o.s. . The e.o.s. at $\rho \sim 10^{14\text{-}15}$ gm/cc contains many uncertainties and has improved a lot in recent years - but not sufficiently to explain the SN.

Numerical calculations did not end in mass ejection but in a

'standing wave' which did not propagate into the envelope.

The energy/gm is sufficient in principle for ejection but present day calculations cannot simulate a SN.

It is not know why the efficiency of the ejection and energy transfer is so high.

ν ejection:

$$\sigma_\nu(\mathrm{cm}^2) \sim \sigma_0 E_\nu^2(\mathrm{MeV})$$

$$\sigma_0 \sim 10^{-44}\,\mathrm{cm}^2$$

At the density of neutron stars $n=10^{39}$/cc $\Rightarrow$ $\lambda \sim 10^5$cm

$\lambda \sim$ R(neutron star)/10

Neutrinos do not escape freely from the core of a neutron star

Neutrino pressure (like photon radiation pressure) is not enough to cause mass ejection

Actually, for $\rho \sim 10^{12}$gm/cc the ν remain captured in the core.

The Raighly Taylor instability

The dominant reaction in the neutrinosphere is

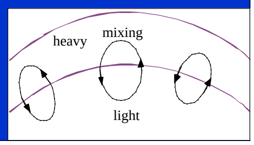
$$p + e^- \Leftrightarrow n + \nu$$

escapes

Since the ν's escape, the balance in the above reaction moves to the right - hence more neutrons

The matter below remains rich in protons, electrons and ν's (electrons & ν are leptons).

The RT instability leads to convection and inversion of the layers. The light floats and the heavy sinks. This process releases the trapped neutrinos.



The out moving shock heats the matter and increases the entropy.

Competition: neutrino losses de stabilizes while entropy gradient (due to shock) stabilizes

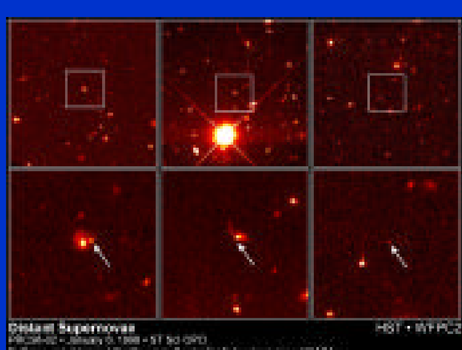
Present situation:

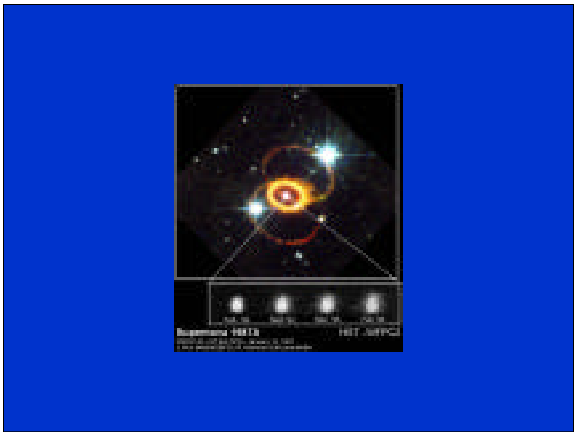
Is the mixing time scale appropriate?

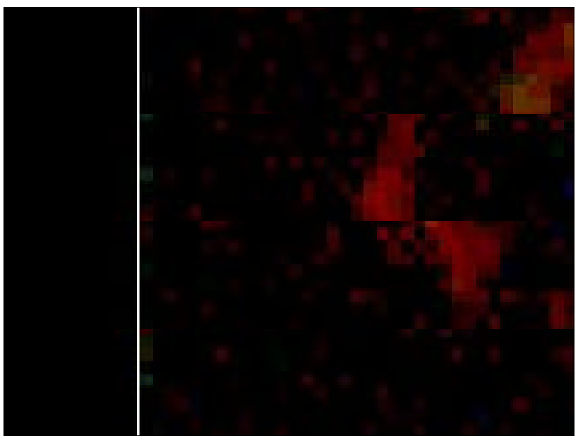
Is the number of release neutrino sufficient to eject the envelop?

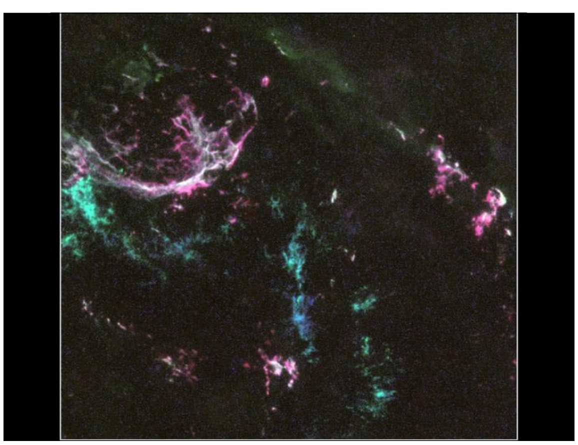
At present: no working model for SN

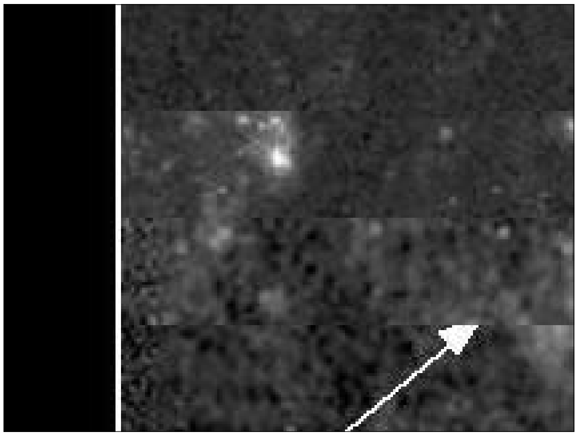
Extreme sensitivity to e.o.s. and other data.

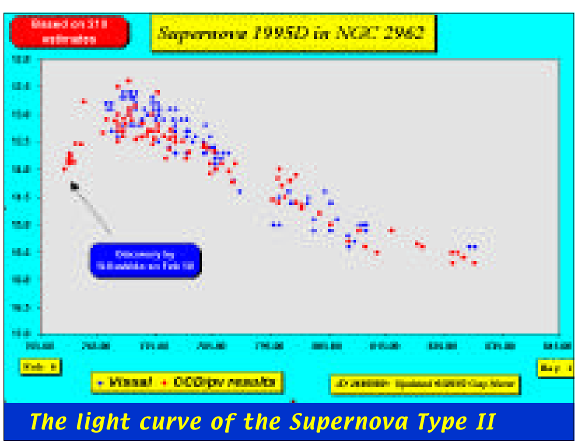











Supernova 1995D in NGC 2962
Visual
CCD/pv results
The light curve of the Supernova Type II


The end!