Радиативные ударные волны и их роль в объяснении загадки Сверхмощных сверхновых

Блинников С.И.[1,2,3]

[1] **ИТЭФ (НИЦ Курчатовский Инст.), Москва**

[2] **ВНИИА, Москва**

[3] **Kavli IPMU, Tokyo University**

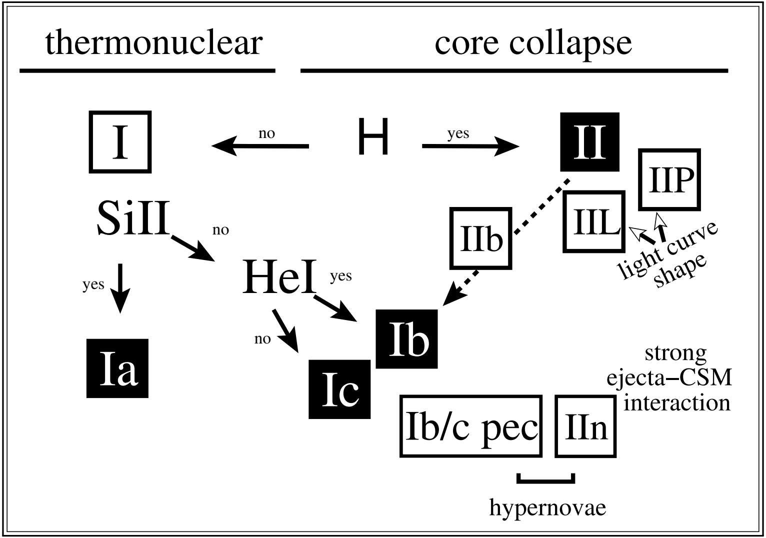
Школа Нелинейные волны, февраль 2016

Supernova SN1994D in NGC4526

Shocks are not important for light in “Nobel prize” SNe Ia

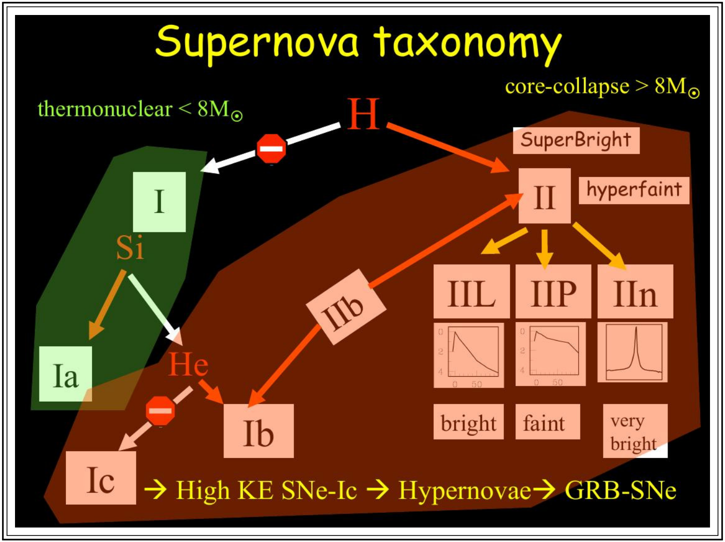
Supernova Classification, Классификация сверхновых

by Massimo Turatto



SN taxonomy

by Massimo Della Valle



Supernova taxonomy

thermonuclear < 8M$_\odot$

core-collapse > 8M$_\odot$

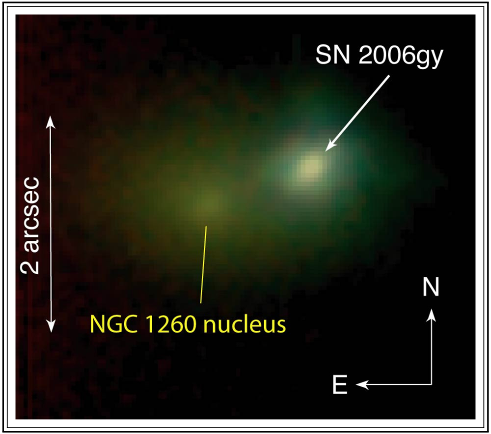
→ High KE SNe-Ic → Hypernovae→ GRB-SNe

SN 2006gy

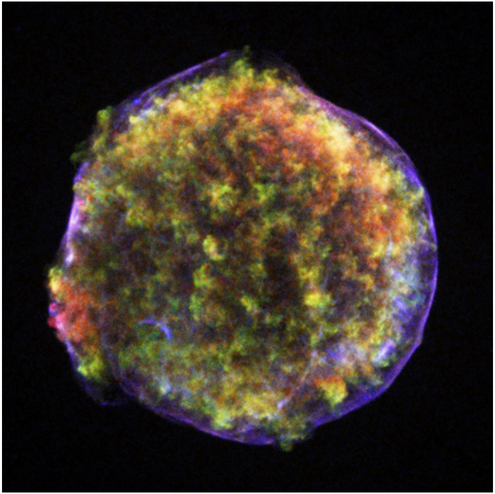
Ofek et al. 2007, ApJL

Smith et al. 2007, ApJ

Shocks are vital for explaining light of those superluminous events for many months…



SNR Tycho in X-rays (Chandra)

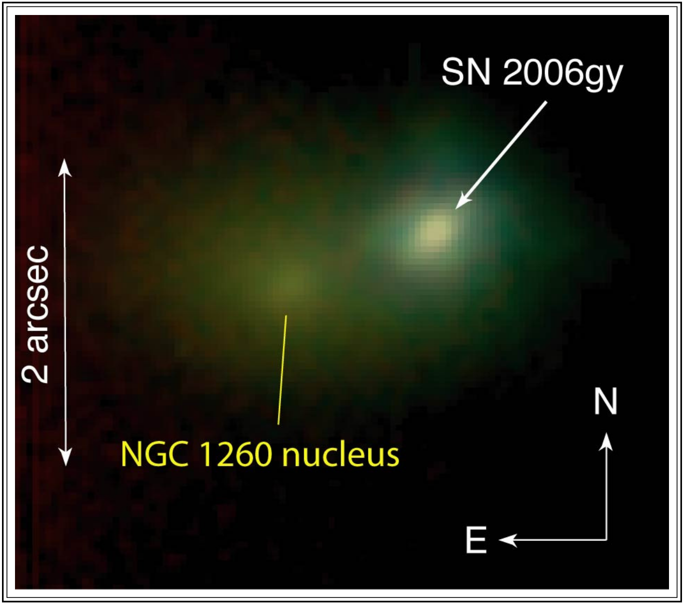


...and thousands of years in SNRs

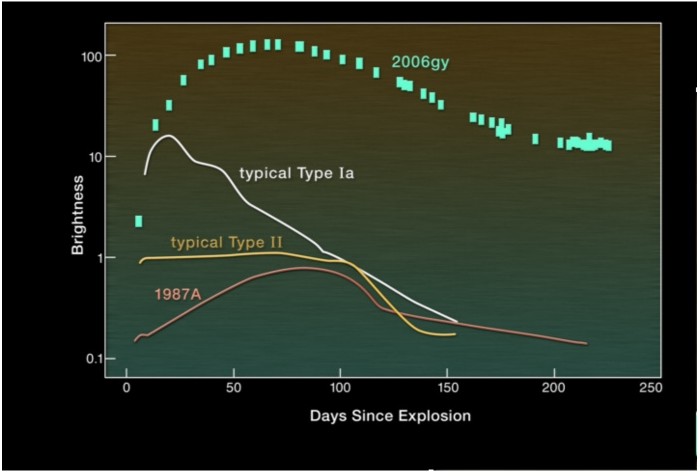
Supernovae: order of events

- Core collapse **(CC)** or explosion
- Neutrino/GW signal, accompanying signals
- Shock creation **if any**, propagation and entropy production inside a star
- Shock breakout (!)
- Diffusion of photons and cooling of ejecta

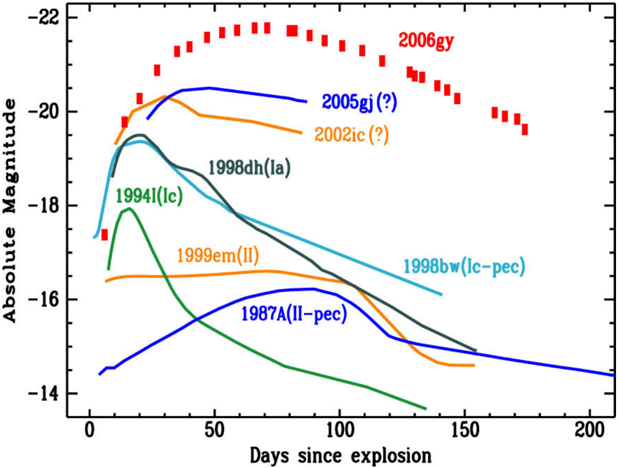
SN 2006gy и ядро её галактики



Так писали ∼10 лет назад: Brightest. Supernova. Ever. – N.Smith

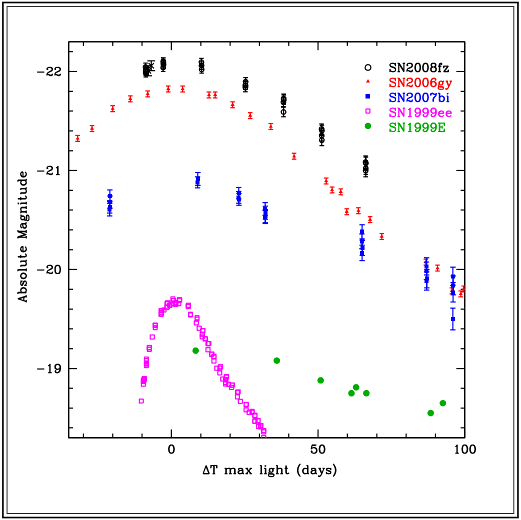


Это была самая мощная (Most Luminous) SN в 2006, но не теперь



Теперь открыто много SN ещё более мощных

Extremely luminous Type IIn SNe

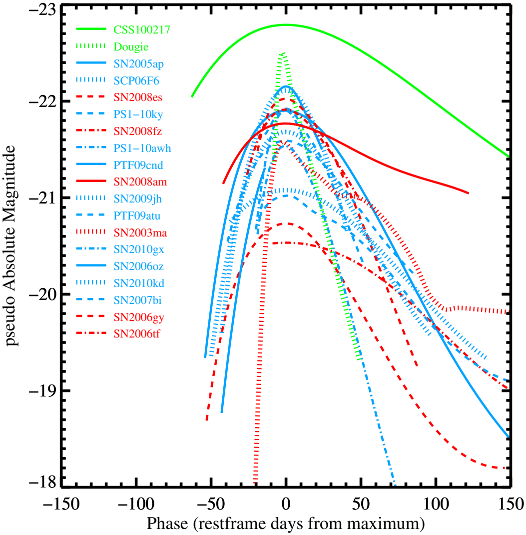


V-band
(Drake et al. 2010)

SN1987A and a typical SNII below the frame!

SLSNe – широкий диапазон

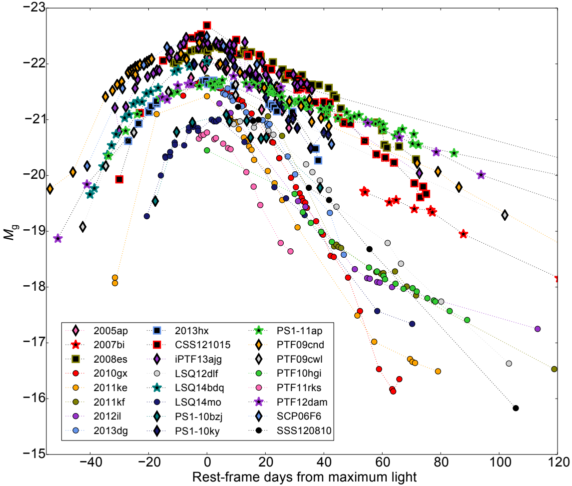
R.Quimby et al. 2013



Hydrogen-poor super-luminous supernovae

M.Nicholl et al. 2015

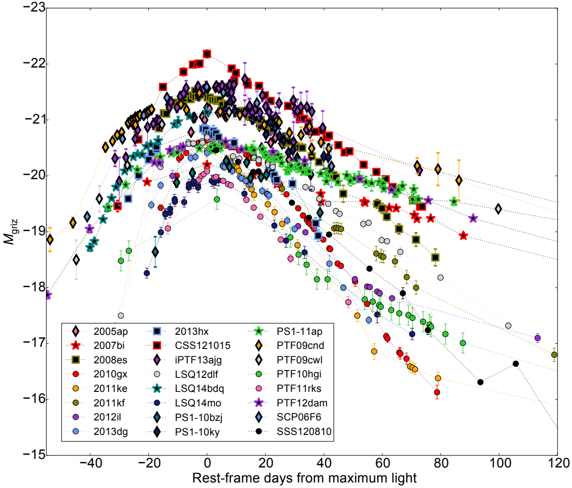
g-band light curves



Безводородные Сверхмощные сверхновые

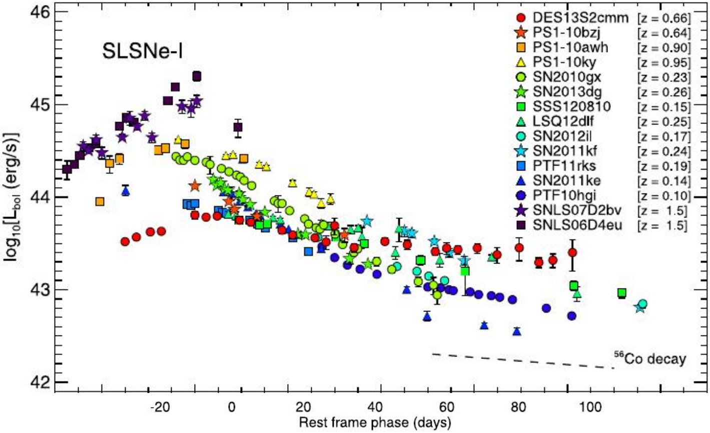
M.Nicholl et al. 2015

griz псевдоболометрические кривые блеска



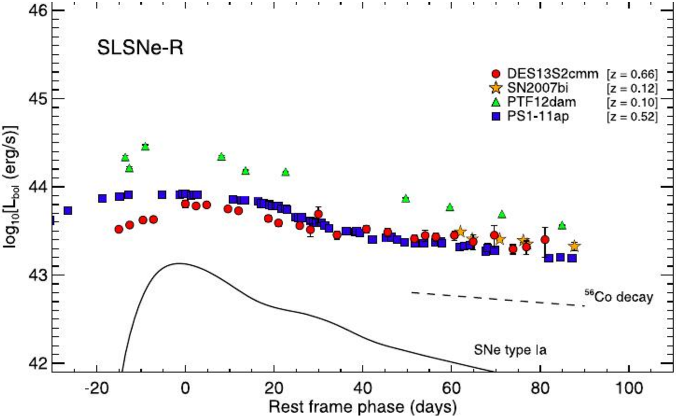
Другой набор и другие единицы, SLSN-I

A.Papadopoulos et al. 2015



SLSN-R – slow decline

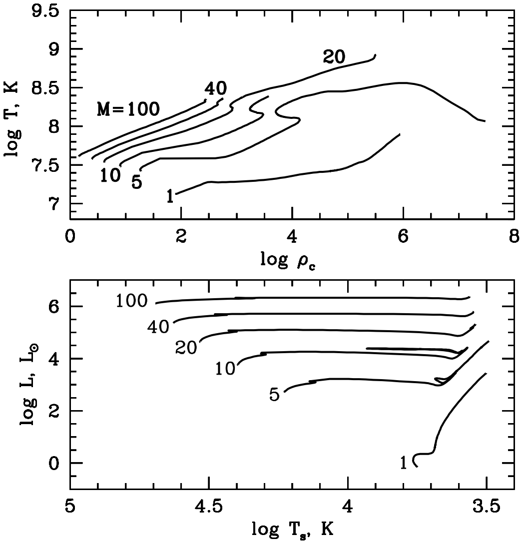
A.Papadopoulos et al. 2015



Три пути для SLSNe

- Неустойчивость при рождении пар Pair instability Supernovae, **PISN**
- **“Магнитарная”** накачка – нужны миллисекундные периоды
- Радиативные ***ударные волны*** в окружающей плотной оболочке, **PPISN**

A bit on stellar evolution



One can notice a trend: $T_c \propto \rho_c^{1/3}$.

Mechanical equilibrum

A very crude order-of-magnitude estimate for the attraction force of two halves of a star is

$$F \sim \frac{G_{\mathrm{N}} M^2}{4R^2},$$

this force must be balanced by a gradient of pressure P.
On the surface P is virtually zero, and in the center

$$P_c = \frac{F}{S} = \frac{F}{\pi R^2}.$$

Central Pressure

Omitting all coefficients of order unity, pressure and density in the center are:

$$P_c \simeq \frac{G_{\rm N} M^2}{R^4},$$

$$\rho_c \simeq \frac{M}{R^3},$$

and we find

$$\boldsymbol{P_c \simeq G_{\rm N} M^{2/3} \rho_c^{4/3}}.$$

On hydrodynamical instability

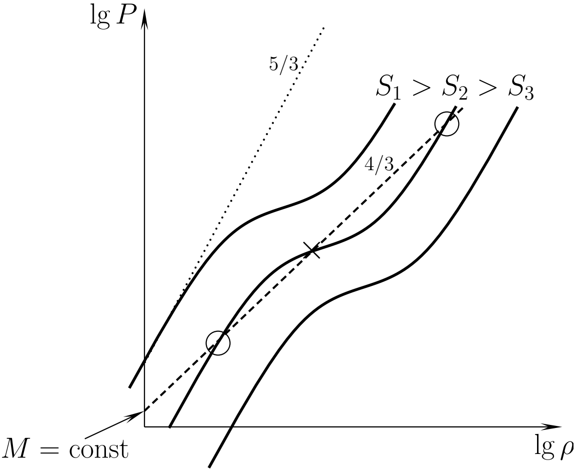
Equilibrium requires (in Newtonian gravity):

$$P_c \simeq G_{\mathrm{N}} M^{2/3} \rho_c^{4/3}.$$

This implies that adiabatic exponent $\gamma < 4/3$ may lead to a hydrodynamical instability.

Hydrodynamical stability

Mechanical stability



Relativistic particles lead to $\gamma \to 4/3$

We have $\gamma \sim 4/3$ due to high entropy S (photons and e^+e^- pairs).
At low $S \to 0$ we have $\gamma \to 4/3$ due to high Fermi energy of degenerate electrons at high density ρ.

$T_c \propto M^{2/3}\rho_c^{1/3}$ in non-degenerate stars

So if we have a classical ideal plasma with

$$P = \mathcal{R}\rho T/\mu,$$

where $\mathcal{R}$ is the universal gas constant, and μ – mean molecular mass,

$$T_c \simeq \frac{G_{\rm N} M^{2/3} \rho_c^{1/3} \mu}{\mathcal{R}}.$$

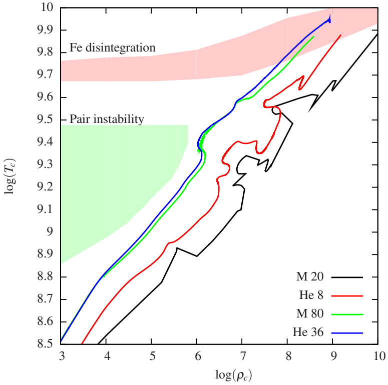
Thus,

$$\boldsymbol{T_c \propto \rho_c^{1/3}}$$

The same 1/3 power for radiation-dominated massive stars (but with $M^{1/6}$).

Массивные звёзды с He-ядрами

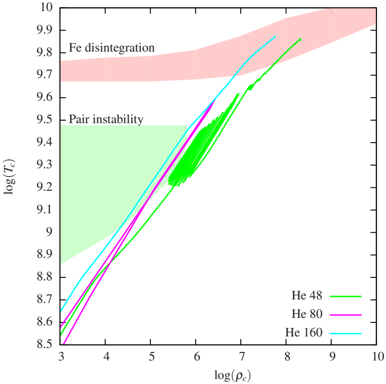
автор Roni Waldman



Каждая строка помечена “M” для звездных моделей и “He”, для моделей с гелиевыми ядрами, с последующей цифрой для массы модели или ядра. Здесь звёзды, которые достигают коллапса избегая нестабильности при рождении пар.

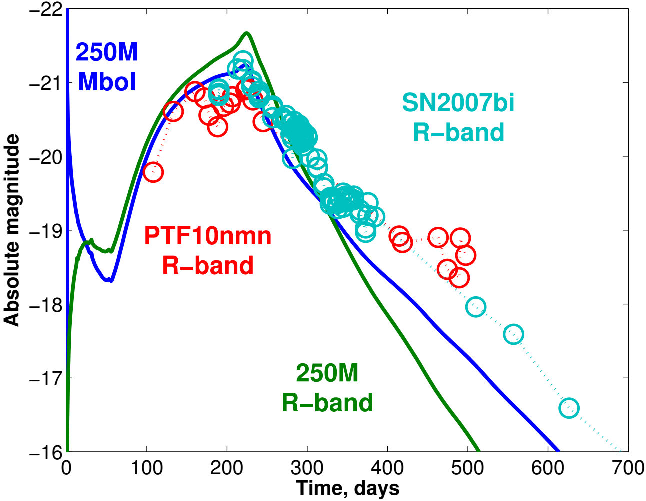
3 варианта для pair-instability

by Roni Waldman



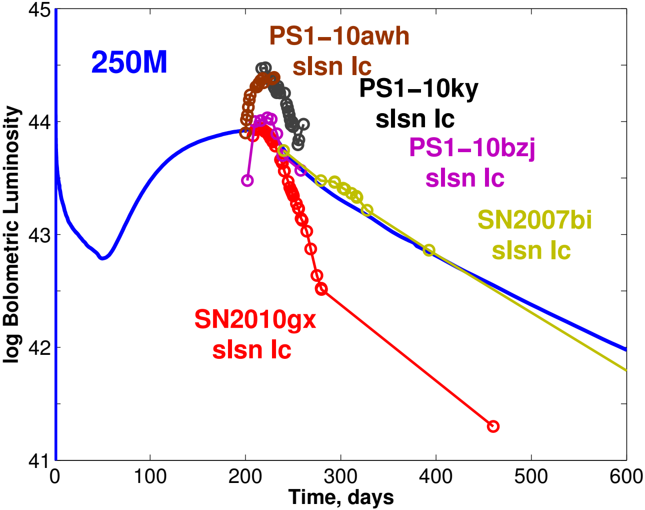
Здесь только He ядра, попадающие в зону неустойчивости

PISN: A. Kozyreva, SB, Langer, Yoon, 2014



$M_{\rm in}/M_{\rm f} = 250/169$, $E_{\rm expl} = 70$, $E_{\rm kin} = 44$, Mass of ^{56}Ni $= 19 M_{\odot}$

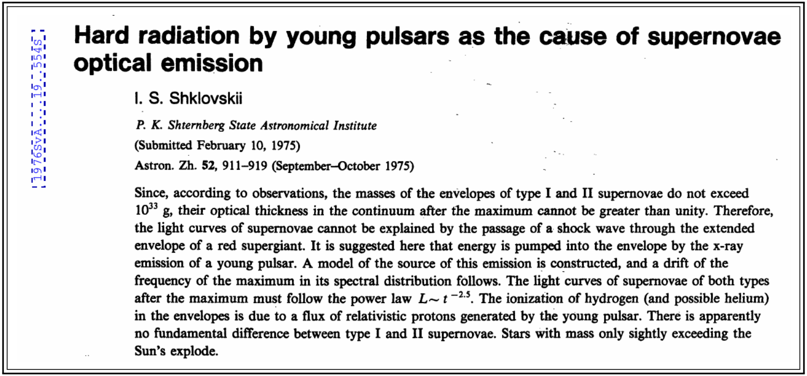
PISN: A. Kozyreva, SB, Langer, Yoon, 2014



Ясно, что некоторые из SLSNe не являются PISN.

Пульсарная накачка сверхновых: старая идея

I.S. Shklovskii, Astron. Zh. 49, 913 (1972) [Sov. Astron. 16, 749 (1973)]
I.S. Shklovskii, Astron. Zh. 52, 911 (1975) [Sov. Astron. 19, 554 (1976)]
Идея Шкловского основывалась на работах
Ostriker, J. P., Gunn, J. E. 1969. On the Nature of Pulsars. I. Theory. The Astrophysical Journal 157, 1395.
G.S. Bisnovatyi-Kogan, Astron. Zh. 47, 813 (1970) [Sov. Astron. 14, 652 (1971)] – магнито-ротационный механизм взрыва сверхновой



Hard radiation by young pulsars as the cause of supernovae optical emission

I. S. Shklovskii

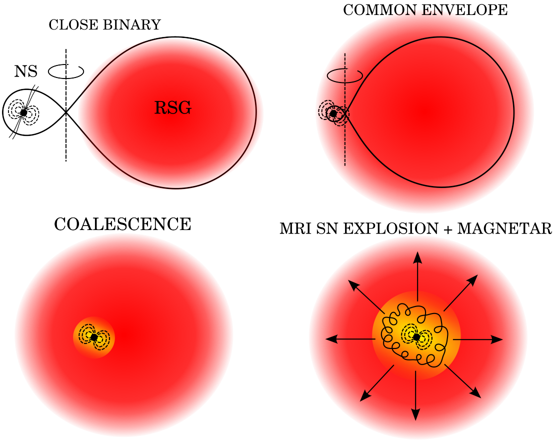
P. K. Shternberg State Astronomical Institute

(Submitted February 10, 1975)
Astron. Zh. **52**, 911–919 (September–October 1975)

Since, according to observations, the masses of the envelopes of type I and II supernovae do not exceed 10^{33} g, their optical thickness in the continuum after the maximum cannot be greater than unity. Therefore, the light curves of supernovae cannot be explained by the passage of a shock wave through the extended envelope of a red supergiant. It is suggested here that energy is pumped into the envelope by the x-ray emission of a young pulsar. A model of the source of this emission is constructed, and a drift of the frequency of the maximum in its spectral distribution follows. The light curves of supernovae of both types after the maximum must follow the power law $L \sim t^{-2.5}$. The ionization of hydrogen (and possible helium) in the envelopes is due to a flux of relativistic protons generated by the young pulsar. There is apparently no fundamental difference between type I and II supernovae. Stars with mass only sightly exceeding the Sun's explode.

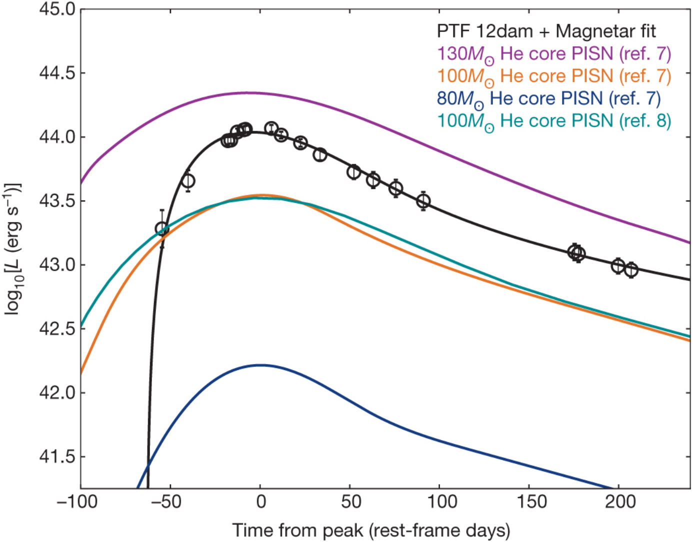
“Магнитарная” накачка сверхновой

Сценарий



Barkov M.V. & Komissarov S.S., *Mon.Not.Roy.Astron.Soc.*, 2011, **415**, pp.944-958

Болометрические кривые блеска и “Магнитарный” фит для PTF 12dam, Nicholl’ea, 2013



Эти “Магнитарные” фиты основаны на слишком упрощенных моделях

На самом деле используется 0D (однозонная, а не 1D!) модель по A.Jerkstrand, на основе аналитической модели Арнетта для радиоактивных накачки сверхновых.

См. код здесь: Magnetar light curve fitting tool (Matlab/Octave версия на вебстранице):

`star.pst.qub.ac.uk/webdav/public/ajerkstrand/Codes/Genericarnett/`

Ссылка: Inserra, Smartt, Jerkstrand et al. 2013

Inserra et al 2013

THE ASTROPHYSICAL JOURNAL, 770:128 (28pp), 2013 June 20

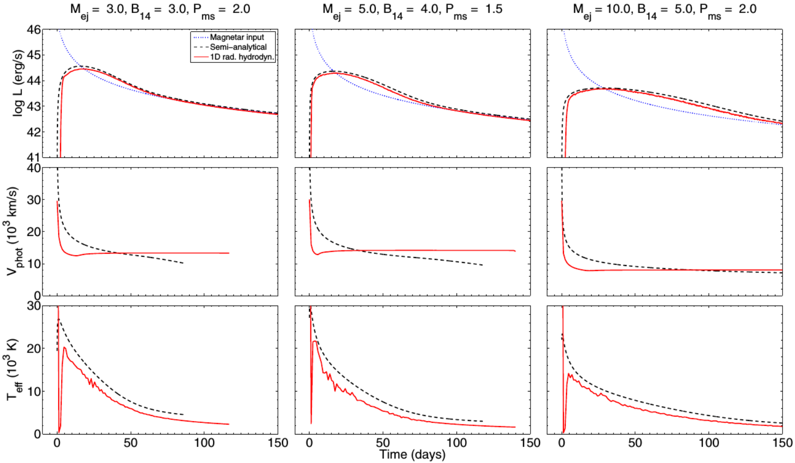
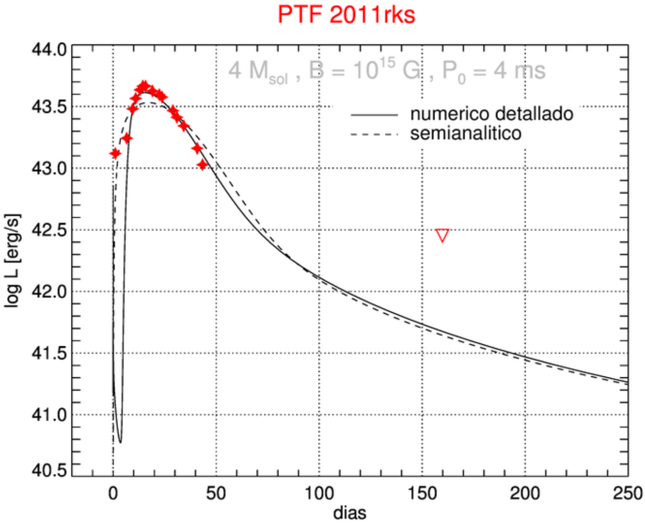


Figure 17. Comparison of light curves, photospheric velocities, and photospheric temperatures from our semi-analytical model (black dashed) and the on
radiation hydrodynamical simulations of Kasen & Bildsten (2010, red solid). Also shown is the input magnetar energy (blue dotted line).

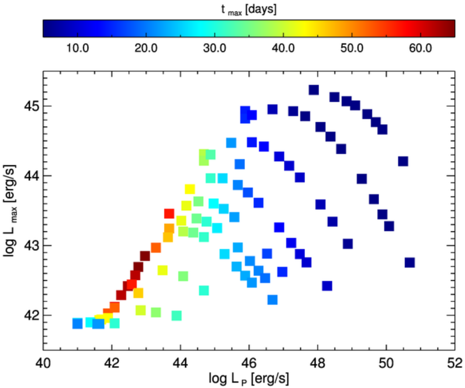
Кривая блеска и Магнитарный фит для PTF 2011rks

Автор: Mariana Orellana



Зависимость светимости от Пульсарной накачки

Автор: Mariana Orellana



Детали см. в статье M.C. Bersten, O. Benvenuto, M.Orellana, K.Nomoto, 2016 ApJ.

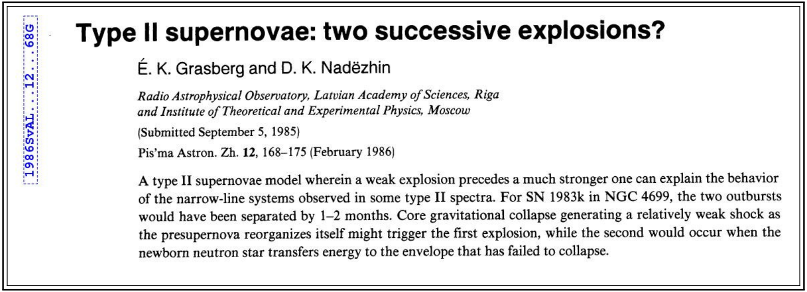
Бадьин, Барков: Почему примитивная “Магнитарная” модель не работает?

Энергия торможения вращения пульсара переходит в давление релятивисткой плазмы и в работу на ускорение слоя, т.е. в кинетическую энергию.

Не в светимость! – работа Д.Бадьина – готовится к печати

Третий путь к SLSN – двойной взрыв: старая идея для SNIIn

Грасберг и Надёжин (1986)



1986SvAL...12...68G

Type II supernovae: two successive explosions?

É. K. Grasberg and D. K. Nadëzhin

Radio Astrophysical Observatory, Latvian Academy of Sciences, Riga
and Institute of Theoretical and Experimental Physics, Moscow

(Submitted September 5, 1985)

Pis'ma Astron. Zh. **12**, 168–175 (February 1986)

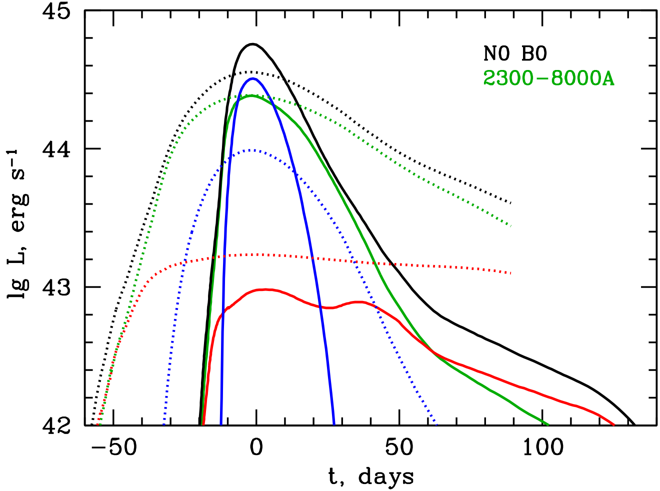
A type II supernovae model wherein a weak explosion precedes a much stronger one can explain the behavior of the narrow-line systems observed in some type II spectra. For SN 1983k in NGC 4699, the two outbursts would have been separated by 1–2 months. Core gravitational collapse generating a relatively weak shock as the presupernova reorganizes itself might trigger the first explosion, while the second would occur when the newborn neutron star transfers energy to the envelope that has failed to collapse.

Мы можем воспроизвести диапазон SLSNe в моделях взаимодействия ударной волны с окружающей средой при умеренной энергии

Для SLSNe предлагались модели с энергиями взрыва в десятки раз выше обычных, в десятки раз более массивные и с огромным количеством радиоактивного ^{56}Ni.
Наш 1D лагранжев код STELLA с многогрупповым переносом излучения позволяет получить более экономную модель.

Последняя статья с нашими результатами Sorokina, Blinnikov, Nomoto, Quimby, Tolstov 2016, ApJ (arXiv:1510.00834).

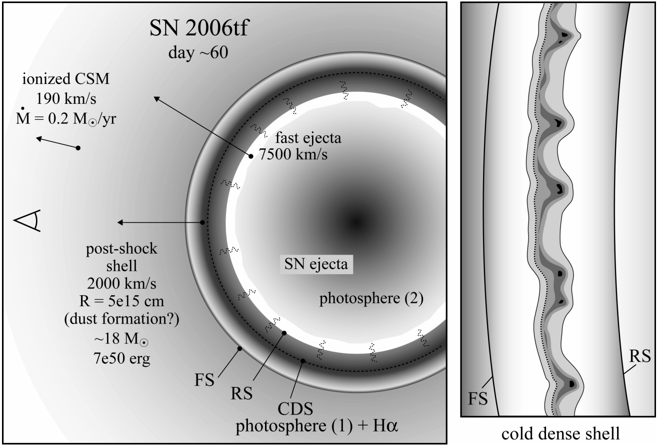
STELLA воспроизводит диапазон SLSN: пример на двух моделях



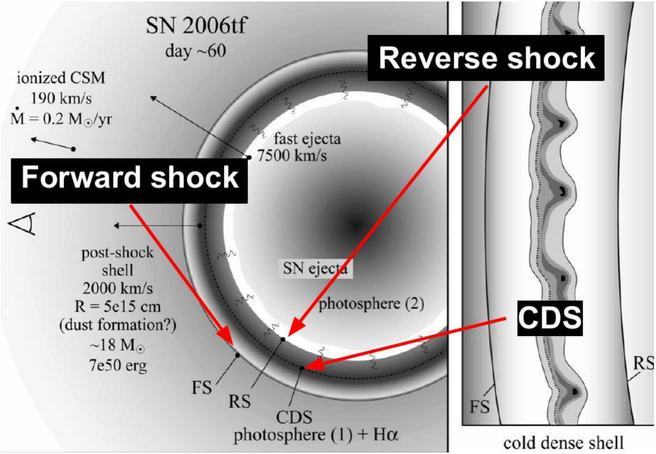
Энергии взрывов всего в 2 - 4 раза выше средних для сверхновых

Радиативные ударные волны в плотной околозвёздной среде – мощный источник видимого света SLSNe

схематичная картинка – a cartoon (Credit Smith, Chornock, et al.):



Радиативные ударные волны: мощный источник света в SLSNe. Холодный плотный слой



Некоторые оценки для светимости

$$L = 4\pi\sigma T_{\rm eff}^4 R_{\rm ph}^2$$

for the age of supernova $t = 10$ d and typical velocity at photosphere level $u = 10^9$ cm/s (i.e. 10 thousand km/s) we get $R_{\rm ph} = ut \approx 10^{15}$ cm, and if a typical $T_{\rm eff} \sim 10^4$ K, then $L \sim 10^{43}$ erg/s.
Luminosity L goes down in some weeks, thus, ordinary, non-interacting supernovae produce $\sim 10^{49}$ ergs in photons during the first year after explosion, while $\sim 10^{51}$ ergs remain in the kinetic energy of ejecta in “standard” SN explosions.

This energy is radiated much later, during millennia after the explosion (mostly in X-rays) by the supernova remnant in the shocks produced by ejecta in ordinary interstellar medium with the number density ~ 1 cm^{-3}. If the density of CSM is billion times higher, then a large fraction of the kinetic energy will be radiated away much faster, on a time scale of a year and the photons will be much softer than X-ray, they will be emitted mostly in visible or ultraviolet range.

Температура фотосферы

We may have the same typical $T_{\text{eff}} \sim 10^4$ K, while $R_{\text{ph}} \sim 10^{16}$ cm is much larger and the luminosity goes up approaching $L \sim 10^{45}$ erg/s for some period of time. Thus a superluminous supernova (SLSN) can be produced for the energy of explosion on the standard scale of 1 foe $\sim 10^{51}$ ergs, but now a major fraction of this energy is lost during the first year.

Механика неупругого удара

If we have a blob of matter with mass m_1 and momentum $\mathbf{p_1}$ its energy is

$$E_1 = \frac{\mathbf{p_1}^2}{2m_1}. \tag{1}$$

If it is colliding with another blob with mass m_0 and zero momentum we get for the final energy of two merged blobs in a **fully inelastic collision**

$$E_2 = \frac{\mathbf{p_1}^2}{2(m_1 + m_0)}. \tag{2}$$

The momentum is conserved, but the energy in amount $E_1 - E_2$ is radiated away, since $E_2 < E_1$. If $m_0 \ll m_1$ only a tiny fraction of E_1 is radiated, but if $m_0 \gg m_1$, then $E_2 \ll E_1$ and almost all initial E_1 is radiated away.

Маломассивный выброс и тяжёлая оболочка

This means that collisions of low mass and fast moving ejecta with heavy (dense) slowly moving blobs of CSM are efficient in producing many photons. Of course one should remember that in this case the momentum of the two merged blobs may be different from the initial $\mathbf{p}_1$ if we have a directed flux of newborn photons which carry some net momentum away.

There is no much sense in evaluating this effect using the order-of-magnitude estimates because the details of the production of photons may be complicated. The degree of “inelasticity” of the collision depend on the pattern of hydrodynamic flow and on the properties of emission/absorption of the plasma, e.g. on its composition. Anyway, those details and conservation of momenta and energy must be taken into account in full radiation hydrodynamic simulations.

Давление за фронтом

Now let us find the temperature behind the shock front. Again on the level of simple estimates for the pressure behind the shock front P_s we have

$$P_s \sim \rho_0 D^2 = n_0 m_i D^2 \tag{3}$$

if the density upstream the front is ρ_0, and D is the velocity of the front. The density $\rho = nm_i$ with n number density and m_i averaged mass of ions. The estimate (3) follows from the momentum conservation: the momentum flux is $P + \rho u^2$ for the flow having velocity u, and P is negligible ahead of the front where the matter is cold. More accurate expression for P_s is easily derived from the laws of conservation.

Температура за фронтом

The estimate (3) gives for a non-relativistic plasma with pressure $P = nk_BT$:

$$k_BT_s \sim m_iD^2 \tag{4}$$

which suggests very high temperatures, in keV range and higher for shock velocities larger that a thousand km/s.
Можно вывести “точные” коэффициенты в (4).

Соотношения для ударных волн

We use standard notations for density ρ, velocity u, pressure P, thermodynamic energy E, and define

$$U_1 = \rho,$$

density of momentum

$$U_2 = \rho u,$$

total energy density

$$U_3 = E + \frac{\rho u^2}{2}.$$

We also define fluxes of mass, $F_1 = \rho u$,
of momentum, $F_2 = \rho u^2 + P$,
and of energy $F_3 = (E + \frac{\rho u^2}{2} + P)u$,
and we have a general law of conservation:

$$\frac{\partial \vec{U}}{\partial t} = \frac{\partial \vec{F}}{\partial x}.$$

Соотношения для ударных волн

In a stationary case, i.e. $\partial\vec{U}/\partial t = 0$, we get $\vec{F} = \text{const}$. Introduce

$$j \equiv \rho u = \text{const}, \qquad V \equiv \frac{1}{\rho} \; .$$

From $F_2 = \rho u^2 + P = j^2 V = \text{const}$ we obtain:

$$j^2 V_0 + P_0 = j^2 V_s + P_s \to P_s = P_0 + j^2 (V_0 - V_s) \; ,$$

Subsript “0” for $\rho, \; V, \; u, \; P, \; E$ denotes the initial values upstream (ahead of the shock front), while “s” corresponds to the values downstream, in the shocked matter. It is most convenient to work in the reference frame where the front is at rest, then the speed of the shock D is just u_0, because by definition it is measured relative the unshocked matter.

Соотношения для ударных волн

Now $F_3 = \text{const}$ gives:

$$(E_0 + \tfrac{1}{2}j^2 V_0 + P_0)u_0 = (E_s + \tfrac{1}{2}j^2 V_s + P_s)u_s$$

If we replace here $u_i \to jV_i$, we get:

$$(E_0 + \tfrac{1}{2}j^2 V_0 + P_0)jV_0 = (E_s + \tfrac{1}{2}j^2 V_s + P_s)jV_s \ .$$

From here

$$E_0 V_0 + \tfrac{1}{2}j^2 V_0^2 + P_0 V_0 = E_s V_s + \tfrac{1}{2}j^2 V_s^2 + P_s V_s \ ,$$

and

$$(E_0 + P_0)V_0 + \tfrac{1}{2}j^2(V_0^2 - V_s^2) = (E_s + P_s)V_s \ .$$

Соотношения для ударных волн

But $(V_0^2 - V_s^2) = (V_0 - V_s)(V_0 + V_s)$ and $P_s = P_0 + j^2(V_0 - V_s)$ obtained above implies $V_0 - V_s = (P_s - P_0)/j^2$, so j^2 cancels in numerator and denominator:

$$(E_0 + P_0)V_0 + \tfrac{1}{2}j^2 \frac{(P_s - P_0)}{j^2}(V_0 + V_s) = (E_s + P_s)V_s \; .$$

Thus,

$$\left(E_0 + \frac{P_0 + P_s}{2}\right) V_0 = \left(E_s + \frac{P_0 + P_s}{2}\right) V_s \; ,$$

and we obtain a general formula for the compression in the flow (e.g. on a shock front):

$$\frac{V_s}{V_0} = \frac{2E_0 + P_0 + P_s}{2E_s + P_0 + P_s} \; .$$

Соотношения для ударных волн

An equation of state $E = E(P, V)$, or $P = P(E, V)$ gives the shock adiabat. For a general equation of state in a strong shock ($P_s \gg P_0,\ E_s \gg E_0$) which is most important in supernova envelopes,

$$\frac{V_s}{V_0} = \frac{2E_0/(P_0 + P_s) + 1}{2E_s/(P_0 + P_s) + 1} \approx \frac{1}{2E_s/P_s + 1} \ ,$$

or

$$\frac{\rho_s}{\rho_0} = \frac{V_0}{V_s} \approx 1 + \frac{2E_s}{P_s} \ ,$$

in general case, and

$$\frac{\rho_s}{\rho_0} = \frac{V_0}{V_s} \approx 1 + \frac{2}{\gamma - 1} = \frac{\gamma + 1}{\gamma - 1} \ ,$$

for the case of $\gamma = \mathrm{const}$ equation of state.

Соотношения для ударных волн

Let $P = (\gamma - 1)E_{\rm tr}$, where $E_{\rm tr}$ is translational internal energy, i.e. kinetic energy of particles in plasma, and let $E = E_{\rm tr} + Q$, where Q is, e.g., ionization potential energy. Then in a strong shock

$$\frac{\rho_s}{\rho_0} = \frac{V_0}{V_s} \approx 1 + \frac{2E_{2\rm tr} + 2Q}{P_s} = 1 + \frac{2}{\gamma - 1} + \frac{2Q}{(\gamma - 1)E_{2\rm tr}} \ ,$$

that is

$$\frac{\rho_s}{\rho_0} = \frac{V_0}{V_s} \approx \frac{\gamma + 1}{\gamma - 1} + \frac{2Q}{(\gamma - 1)E_{2\rm tr}} \ .$$

For $\gamma = 5/3$ this gives

$$\frac{\rho_s}{\rho_0} = \frac{V_0}{V_s} \approx 4 + \frac{3Q}{E_{2\rm tr}} \ ,$$

– formula (3.71) in Zeldovich and Raizer.

Соотношения для ударных волн

We found from conservation of momentum ($F_2 = \text{const}$) that $P_s = P_0 + j^2(V_0 - V_s)$, i.e.

$$j^2 = \frac{P_s - P_0}{V_0 - V_s} \approx \frac{P_s}{V_0 - V_s} = \frac{P_s}{V_0[1 - (\gamma - 1)/(\gamma + 1)]} = \frac{P_s(\gamma + 1)}{2V_0} ,$$

– this is valid for a strong shock, constant γ and small Q. Hence,

$$\rho_0^{\cancel{2}} u_0^2 = \frac{P_s(\gamma + 1)\cancel{\rho_0}}{2} ,$$

that is

$$P_s = \frac{2}{\gamma + 1}\rho_0 u_0^2. \tag{5}$$

Note that γ here must be taken for the gas behind the strong shock since the pressure P_0 is negligible and its equation of state is irrelevant.

Температура за фронтом ударной волны

For a non-relativistic plasma with pressure $P = \mathcal{R}\rho T/\mu$ we get from (5)

$$\rho_0 u_0^2 = \frac{(\gamma+1)\mathcal{R}\rho_s T_s}{2\mu} \ ,$$

so

$$u_0^2 = \frac{(\gamma+1)\mathcal{R}\rho_s T_s}{2\rho_0\mu} = \frac{(\gamma+1)^2\mathcal{R}T_s}{2(\gamma-1)\mu} \ .$$

The postshock temperature T_s for the strong shock, constant γ and small Q is (from the last equation)

$$T_s = \frac{2(\gamma-1)u_0^2\mu}{(\gamma+1)^2\mathcal{R}} \ .$$

For $\gamma = 5/3$ we get

$$T_s = \frac{3u_0^2\mu}{16\mathcal{R}} \ . \qquad (6)$$

Температура за фронтом ударной волны

If we put here $D_8 = u_0/10^8$cm/s, then D_8 is the shock speed in thousand km/s and we get

$$T_s(\mathrm{K}) = 2.25 \times 10^7 \mu D_8^2 \tag{7}$$

in Kelvins or

$$T_s(\mathrm{keV}) = 1.94 \mu D_8^2 \tag{8}$$

in keV. Here $\mu = A/(1+Z)$ for plasma (since $n = n_{\mathrm{baryon}}/\mu = n_{\mathrm{ion}} A/\mu = n_{\mathrm{ion}} + n_e = n_{\mathrm{ion}} + Z n_{\mathrm{ion}}$). Note that a typical value for D in SNe is about 10 thousand km/s, so T will be of order 10^9 K or hundreds keV.

Since $\mathcal{R} \approx k_B/m_p$ where m_p is proton mass, we have

$$k_B T_s \sim m_p D_s^2 . \tag{9}$$

This estimate is the same as used in Eq.(4) if we put $m_i = m_p$.

Обманчивые цифры

In supernova envelopes these numbers are misleading!
In reality plasma in supernova conditions is at least partly relativistic: we have a huge number of photons with $P = aT^4/3$, and so T_s is appreciably lower due to high heat capacity of photon gas. Equations (11, 12), see a couple of slides below, show that with account of radiation for D of order of a thousand km/s and for $\rho \sim 10^{-12}$ gcc we have $T_s = 4.3 \times 10^4$ K, well below X-ray range of temperatures, but high enough to support high L for a long time at large R.

Предупреждение

Using $\gamma = \mathrm{const}$ is a favourite approximation in many papers and simulations in astrophysics, but in supernovae it is very bad one, and almost irrelevant. The value of γ varies due to ionization/excitation of atoms, and changes strongly on the shock front when it goes through the cold layers and heats the plasma so strongly that radiation pressure dominates downstream behind the front. In that case (which is quite general for supernova shock breakout) the formulas (7,8) are not applicable and misleading. The equations for mass, momentum and energy conservation are more complicated for radiative shock waves when one has to account for the transfer of momentum and energy of photons. Nevertheless there are two important limiting cases for strong shocks with radiation when simple expressions can be derived.

Роль излучения

In the first case we may have relatively cold gas upstream with $P_0 \ll P_s$ in the strong shock, and the gas downstream is opaque with the pressure dominated by radiation.

Due to a high heat capacity of photon gas, the temperature behind the front is orders of magnitude lower than in (7),(8).

Let us put radiation pressure for P_s into (5), we get

$$\frac{aT_s^4}{3} = \frac{2}{\gamma + 1}\rho_0 u_0^2. \tag{10}$$

We have $\gamma = 4/3$ for the radiation dominated gas, and, substituting $u_0 = D$, we obtain

$$T_s = \left(\frac{18}{7a}\rho_0 D^2\right)^{1/4}. \tag{11}$$

That is

$$T_s(K) = 4.3 \times 10^4 \rho_{-12}^{1/4} D_8^{1/2}, \tag{12}$$

if we normalize density for $\rho = 10^{-12}$ gcc and take D in units of thousand km/s. The temperature in reality is much less than in (8).

Изотермическая ударная волна

The second important case takes place when the radiation is not trapped, its pressure and momentum may be neglected, but when it is very efficient in heat transport. Now the energy is not conserved, and the energy flux F_3 is not constant any more. Instead of this we may have the constancy of temperature ahead and behind the front. Mass and momentum conservation give as before:

$$P_s = P_0 + j^2(V_0 - V_s). \tag{13}$$

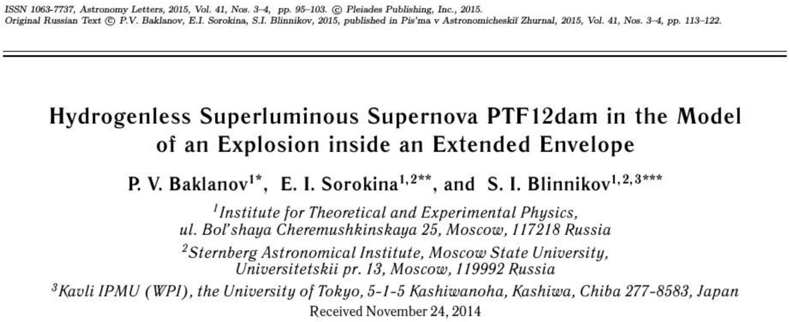
Now both upstream and downstream, the pressure is $P = \mathcal{R}\rho T/\mu$ with the same T, so the strong shock condition, $P_s \gg P_0$ means not a high T behind the front, but $\rho_s \gg \rho_0$, and $P_s \approx \rho_0 u_0^2$ which we get from (13) gives

$$\frac{\rho_s}{\rho_0} = \frac{\mu D^2}{\mathcal{R}T}. \tag{14}$$

Изотермическая ударная волна

The isothermal temperature T here is much less than the temperature found in (7),(8) for adiabatic shocks, hence the compression in isothermal shocks may be orders of magnitude larger than the canonical $(\gamma + 1)/(\gamma - 1)$ of adiabatic shocks. This is a typical situation for formation of cool dense shells in interacting supernovae. The exact value of T and of the compression depends on the details of the properties of plasma with respect to heat conduction, but one should remember that those dense shells may become unstable, and the exact numbers found in idealized accurate plane parallel of spherically symmetric calculation may be not very useful.

Бакланов и др.: Долгая SN PTF12dam



ISSN 1063-7737, Astronomy Letters, 2015, Vol. 41, Nos. 3–4, pp. 95–103. © Pleiades Publishing, Inc., 2015.
Original Russian Text © P.V. Baklanov, E.I. Sorokina, S.I. Blinnikov, 2015, published in Pis'ma v Astronomicheskiĭ Zhurnal, 2015, Vol. 41, Nos. 3–4, pp. 113–122.

Hydrogenless Superluminous Supernova PTF12dam in the Model of an Explosion inside an Extended Envelope

P. V. Baklanov[1]*, E. I. Sorokina[1,2], and S. I. Blinnikov[1,2,3]*****

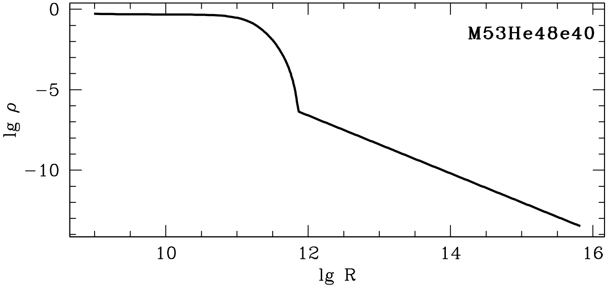
[1] *Institute for Theoretical and Experimental Physics,*
ul. Bol'shaya Cheremushkinskaya 25, Moscow, 117218 Russia

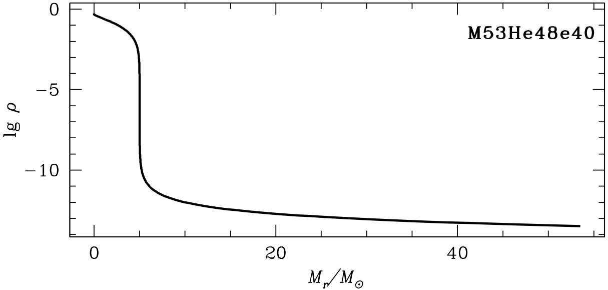
[2] *Sternberg Astronomical Institute, Moscow State University,*
Universitetskii pr. 13, Moscow, 119992 Russia

[3] *Kavli IPMU (WPI), the University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan*

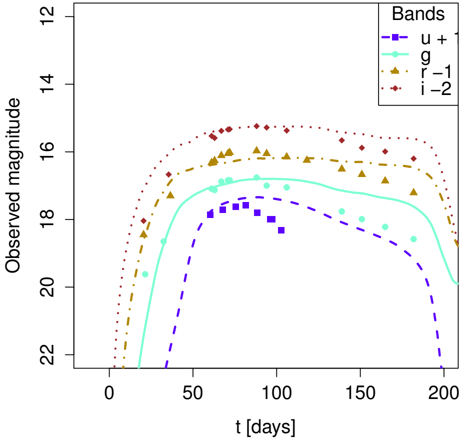
Received November 24, 2014

Assumed preSN and “wind” structure



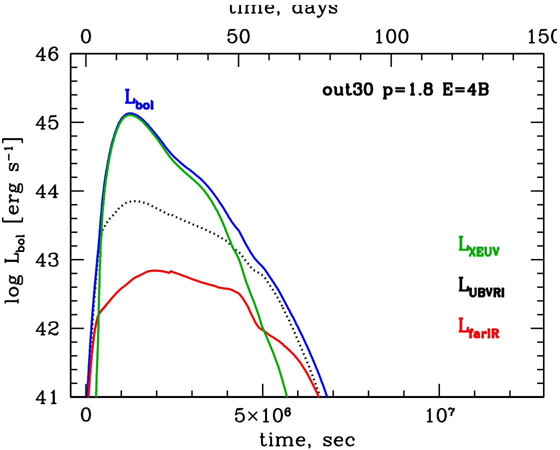


Расчёты и наблюдаемые кривые блеска



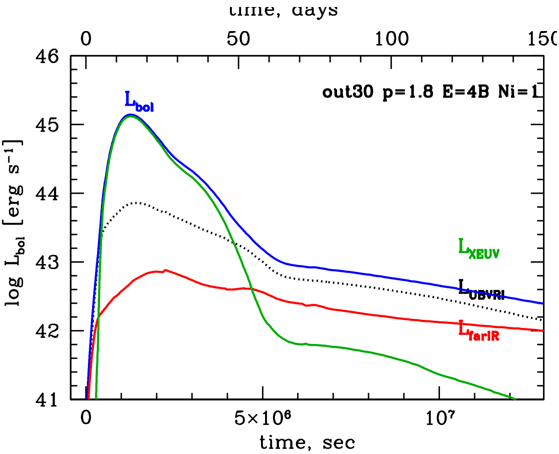
Ejecta 5 $M_\odot$, “wind” 48 $M_\odot$ of He, explosion 4 foe. Perhaps not He, but C/O, and larger mass may be needed for long “tail”. Here radioactive heating may help.

Нагрев ударной волной



no ^{56}Ni

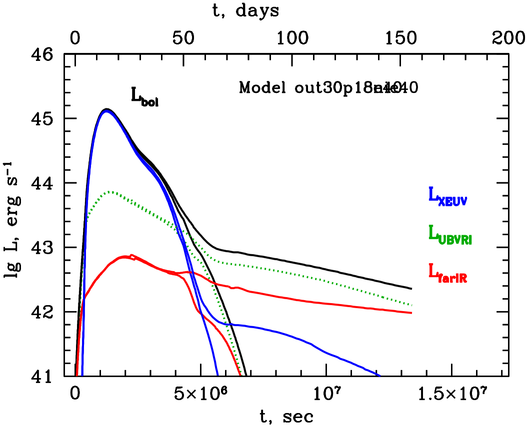
Нагрев ударной волной $+{}^{56}$Ni



$M({}^{56}\mathrm{Ni}) = 1M_{\odot}$ in the ejecta

^{56}Ni vs. Shock wave heating

2 previous plots combined



$M(^{56}\text{Ni}) = 1M_\odot$ added to the ejecta

Трудный случай ASASSN-15lh: экстремально сверхмощная сверхновая

Subo Dong et al. arXiv:1507.03010, Science

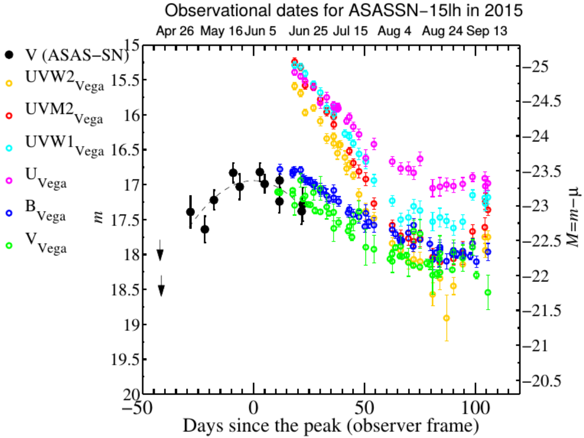
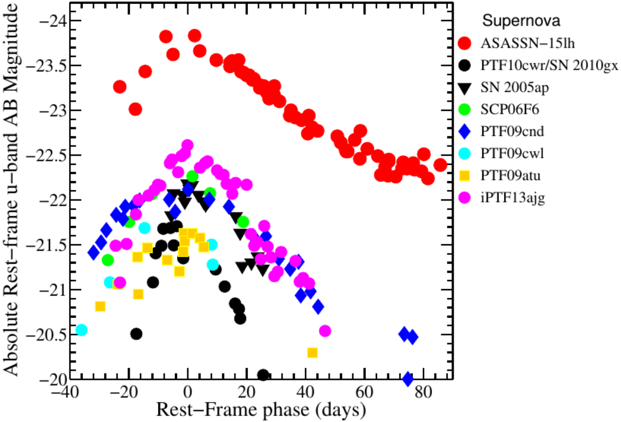
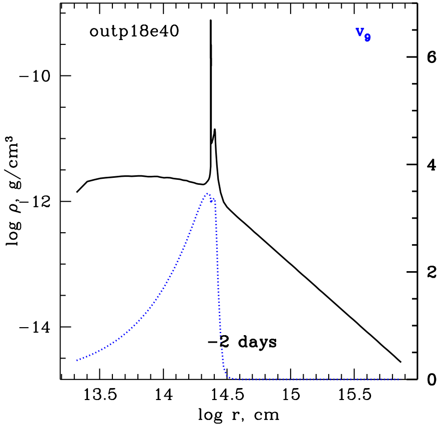


Figure 1. Multi-band light curve of ASASSN-15lh. The *V*-band ASAS-SN light curve is shown as black solid dots, and upper limits are represented by black arrows. *Swift* and LCOGT 1-m data are shown as open circles.

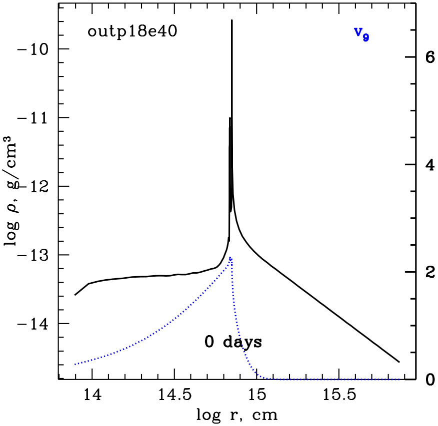
ASASSN-15lh: абсолютные потоки в фильтре u и другие SLSNe



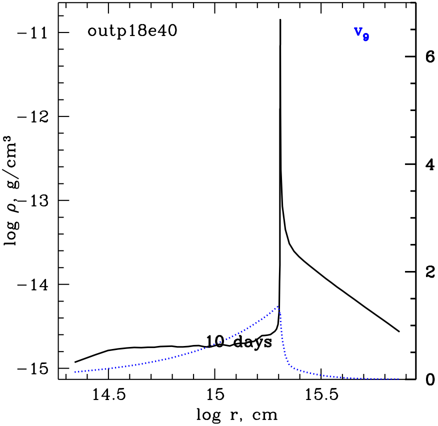
Долгоживущие плотные слои-1 Sorokina et al.



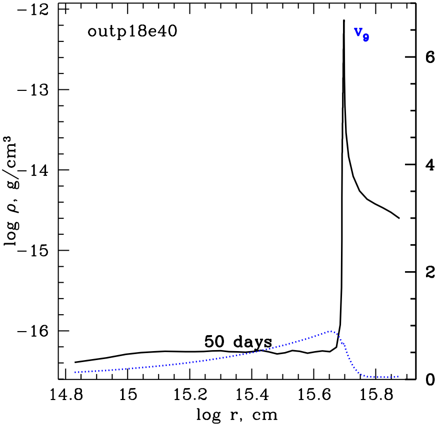
Долгоживущие плотные слои-2 Sorokina et al.



Долгоживущие плотные слои-3 Sorokina et al.



Долгоживущие плотные слои-4 Sorokina et al.



Как поведут себя тонкие слои в 3D реальности?

Вообще говоря, возможны **неустойчивости**, нарушающие картину.

Как они повлияют на производство света?

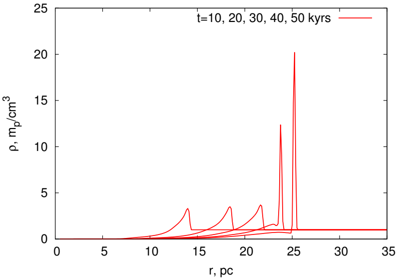
Поэтому мы начинаем программу исследования таких слоёв в многомерии.

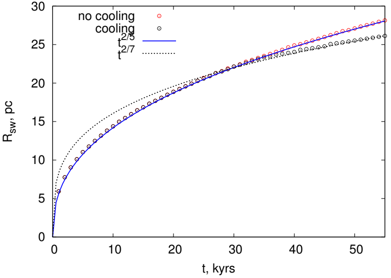
Пока применяем эйлеровы методы.

Для упрощения сначала рассматриваем не сами SLSN, а остатки сверхновых (Supernova Remnants, SNR) на стадии катастрофического охлаждения, когда формируются похожие слои.

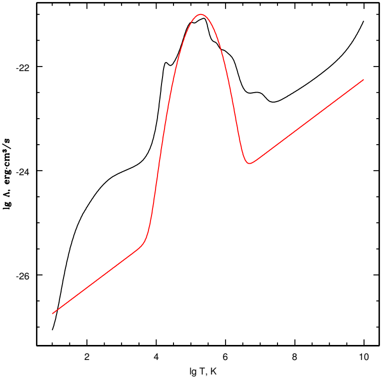
Сильная ударная волна с охлаждением в SNR

- Радиативное охлаждение в приближении оптически тонкой среды ($\tau \ll 1$)
- Возникает скачок плотности $\rho_2/\rho_1 \gg (\gamma+1)/(\gamma-1)$
- Решение переходит от седовского $\propto t^{2/5}$ на радиативное $\propto t^{2/7}$





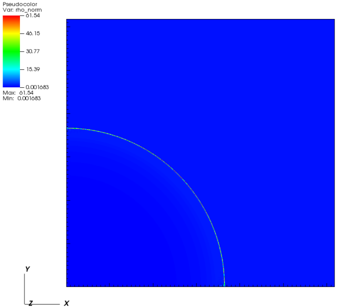
The shape of cooling function



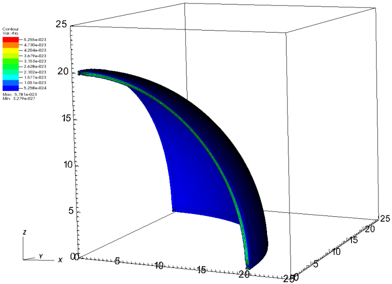
Температурная зависимость функции охлаждения.

Red line is approximation by Straka, and the black one – T.Plewa based on the CLOUDY package.

2D and 3D simulations



Density at $t = 41 \times 10^3$ yrs. Grid 1600x1600, FRONT3D.

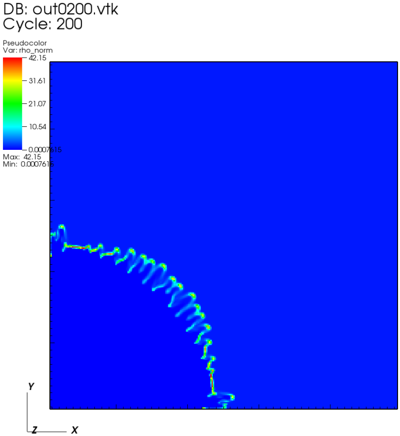


3D simulations. Density at $t = 40 \times 10^3$ yrs. Grid 512^3, FRONT3D.

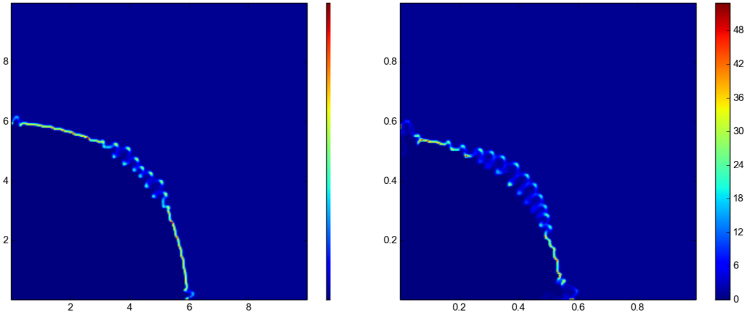
Радиативная ударная волна в 2D

В многомерном случае на стадии сильного радиативного охлаждения сферическая симметрия нарушается – возникает неустойчивость (затравкой которой в представленном расчёте является декартова сетка). Здесь плотность 1 барион/см^3, размер области 80 пк. Расчёт FRONT3D.

Сферическая симметрия не нарушается на сетке $R - \phi$!

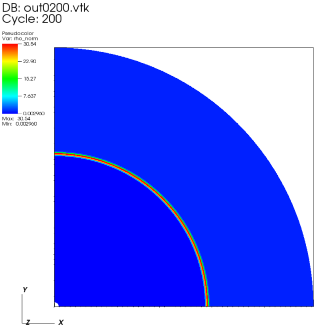


Неустойчивость при разной плотности (более слабый взрыв)

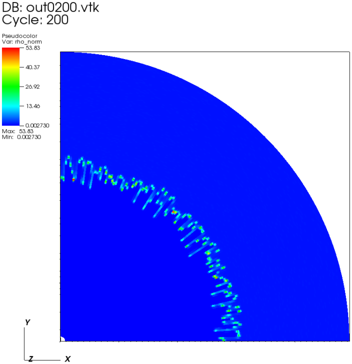


Grid 256x256 for CLOUDY cooling function $n_0 = 1, \gamma = 5/3$, left, and $n_0 = 10, \gamma = 1.4$, right.

Роль сетки: переход к геометрии $R - \phi$ (цилиндрический случай $\partial/\partial z = 0$)

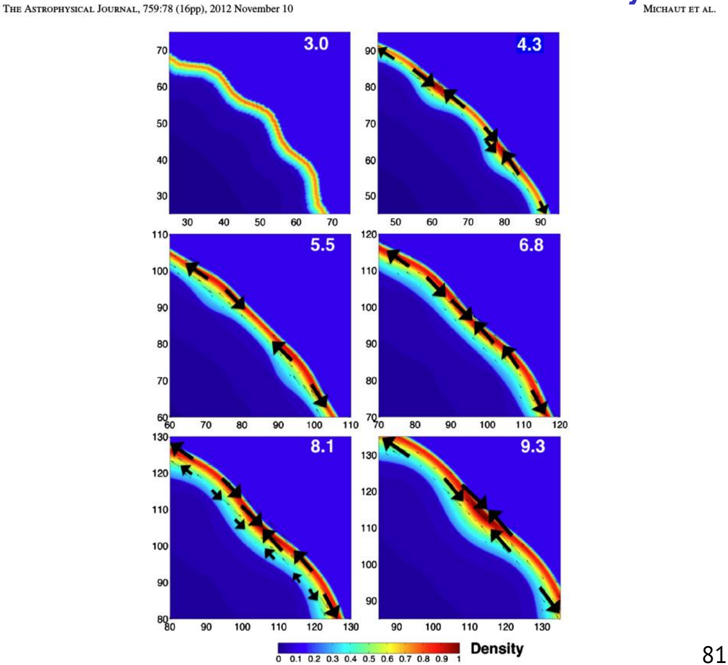


Начальные условия – однородные по ϕ. Момент $t = 200$ тыс. лет. Расчёт на сетке 256x128 ячеек, FRONT3D.



Начальные условия те же + во всём пространстве случайные 5% возмущения в плотности. Сетка и t те же.

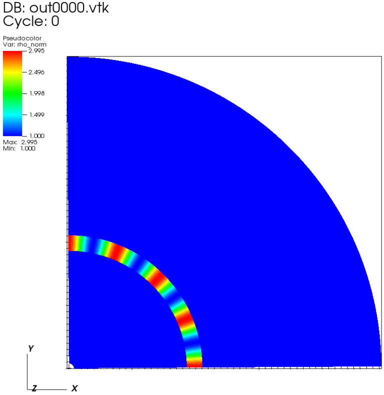
Неустойчивость Вишняка – Vishniac Instability?



The Astrophysical Journal, 759:78 (16pp), 2012 November 10

Michaut et al.

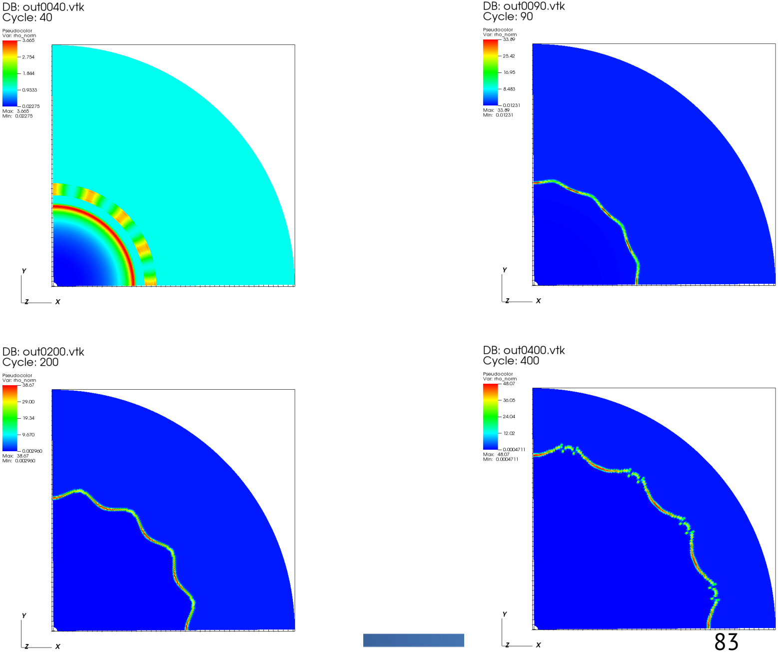
Регулярные возмущения начальной плотности



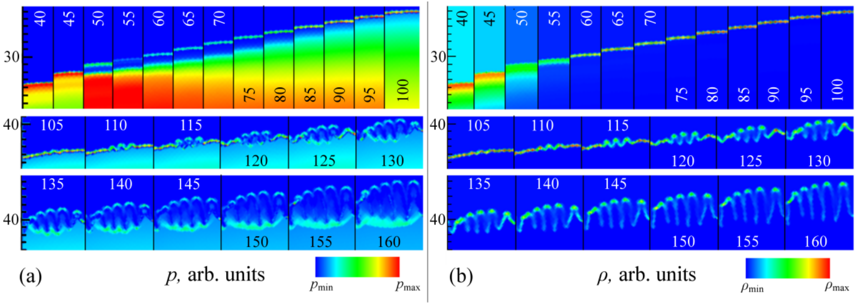
Объяснение неустойчивости – РТ неустойчивость внутренней границы из-за транзиентного ускорения при выравнивании давлений после резкого охлаждения.

Подробности: Badjin et al. arXiv:1512.02037

Неустойчивость Вишняка не развивается (сетка $R - \phi$)



Развитие неустойчивости нового типа



Объяснение неустойчивости – РТ неустойчивость внутренней границы из-за транзиентного ускорения при выравнивании давлений после резкого охлаждения.

Подробности: Badjin et al. arXiv:1512.02037

Выводы

- **Модель радиативной ударной волны – наилучшая для большинства SLSNe.** В ней трудно объяснить некоторые сверхновые с высокой скоростью на фотосфере, слишком долгие кривые блеска или события **ASASSN-15lh SN 2015L**.
- “Магнитарная” модель – обещающая, но пока она не развита.
- Появляются другие модели, например, “Explaining the most luminous supernovae with an inefficient jet-feedback mechanism” A.Gilkis et al. 1511.01471. **Нужны новые идеи!**
- Неустойчивости тонких слоёв между радиативными ударными волнами развиваются при наличии сеточных или физических возмущений.
- Характер развития отвечает не колебательной картине Вишняка (overstability), а скорее тепловой неустойчивости. **Вводим новый тип неустойчивости.**
- Для условий Сверхмощных сверхновых (SLSN) необходим аккуратный учёт переноса излучения с учётом неустойчивости слоя.

Спасибо за внимание!