Сверхновые, похожие на SN1987A (Refsdal, SN 2018hna и др.), и эволюционные пути их образования

Блинников С.И.

доклад на stars-2023

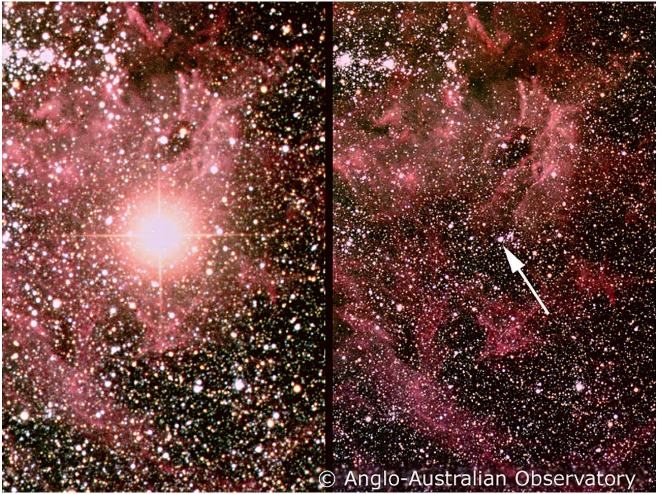
Astronomical introduction to supernovae

S.I.Blinnikov[1,2]

[1] *Institute for Theoretical and Experimental Physics (ITEP), Moscow*

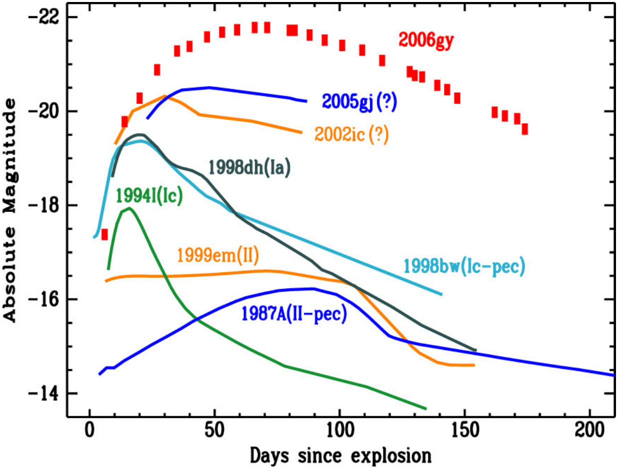
[2] *Sternberg Astronomical Institute (SAI), Moscow*

SN1987A – ближайшая сверхновая, наблюдавшаяся в 20-м веке



Right panel: a blue supergiant as presupernova

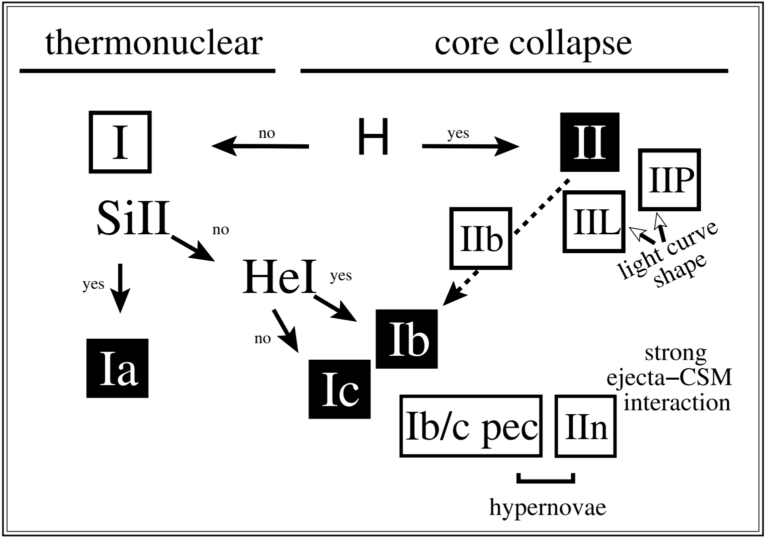
SN1987A was spectacular but very weak in fact



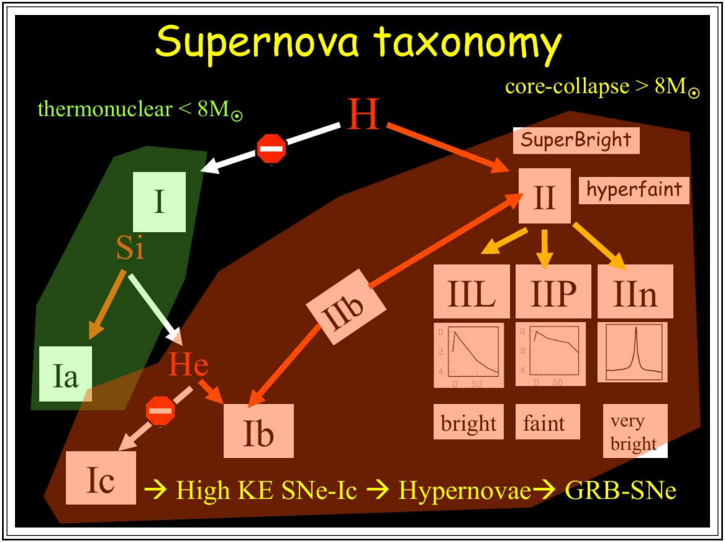
If not ^{56}Ni it would be like -14 mag at maximum light

Supernova Classification

by Turatto



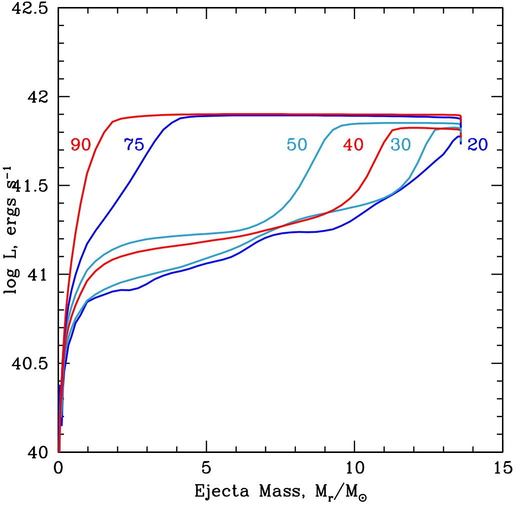
SN taxonomy



Supernova taxonomy
thermonuclear < 8M⊙
core-collapse > 8M⊙
H
SuperBright
II
hyperfaint
I
Si
IIL
IIP
IIn
IIb
Ia
He
Ib
Ic
bright
faint
very bright
→ High KE SNe-Ic → Hypernovae→ GRB-SNe

Formation of LC plateau - L

Imshennik, Nadyozhin, Grassberg (1964-1971)



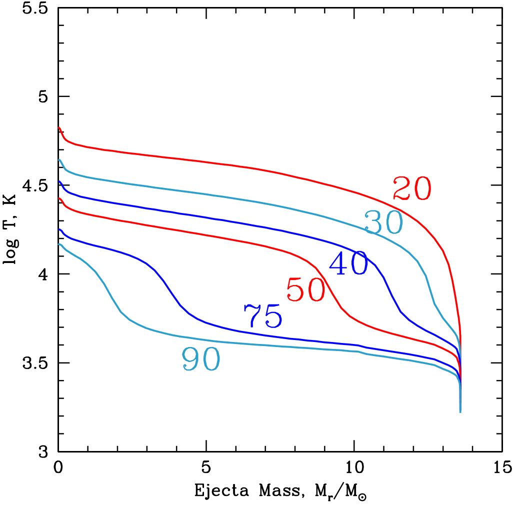
Модель SN 1999em, Бакланов и др. (2005)

Владимир Сергеевич Имшенник

27 сентября 1928, Дебальцево — 7 февраля 2023, Москва

Formation of LC plateau - T

Recombination front moving inside in M_r



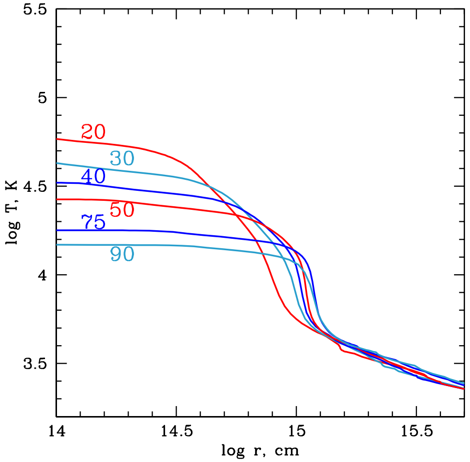
Волна охлаждения и рекомбинации

Type IIP photosphere

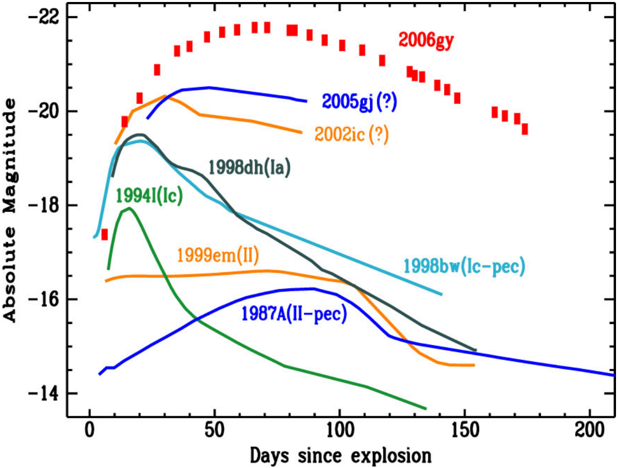
The photosphere is almost at rest - not much expanding in R and later contracting in R

$L = 4\pi\sigma T_{\text{eff}}^4 R^2 \approx$ const

Baklanov, Blinnikov, Pavlyuk (2005)

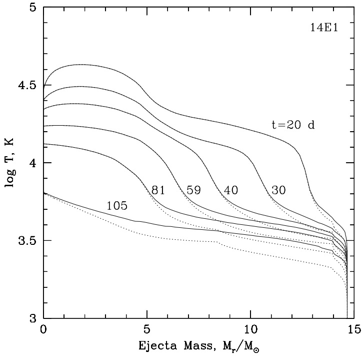


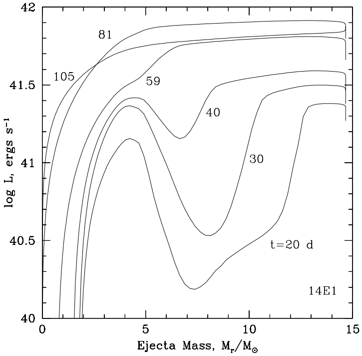
Отличие SN1987A от других SN II было в большой роли ^{56}Ni



Из-за малого радиуса предсверхновой $\sim 50R_{\odot}$ плато было очень низким и коротким.

Профиль $T(m)$ в 87A похож, но $L(m)$ уже другой





Предсказание И.С. Шкловского в 1984

A wonderful prediction made by Shklovskii is the result of his life-long study of the relation of different supernova types to different types of gaseous supernova remnants. Based on the theory of SN light curves, developed by V.S.Imshennik, D.K.Nadyozhin and E.K.Grasberg, Shklovskii predicted in 1984 that supernovae of type II exploding in galaxies similar to the Large Magellanic Cloud **must have low luminosity due to the relatively small radius of SNII progenitors in low metallicity environments**. This prediction was brilliantly confirmed by SN1987A.

Shkloovskii's predictions on SN1987A

Why are there no type II supernovae in irregular galaxies?

I. S. Shklovskiĭ

Institute for Space Research, USSR Academy of Sciences, Moscow

(Submitted March 26, 1984)

Pis'ma Astron. Zh. **10**, 723–725 (October 1984)

Irregular galaxies may lack type II supernovae because these systems are deficient in heavy elements, so that their hot, massive giants produce no observable stellar wind. Accordingly, massive stars undergoing terminal evolution will not be embedded in the dense, extended envelopes that are necessary if the SN II phenomenon is to be detected.

Shklovskii's predictions on SN1987A

It has often been pointed out that the only supernovae we observe in irregular, Magellanic-type galaxies are those of type I. At first glance this circumstance may seem rather a paradox, for Ir galaxies are rich in hot, massive stars, accompanied by clouds of interstellar gas. According to current ideas, type II supernova outbursts represent the terminal evolutionary phase of fairly massive stars ($M > 9\ M_{\odot}$; see Trimble's reviews[1,2]). Why, then, don't we observe type II supernovae exploding in Ir galaxies?

...

I shall now offer an alternative explanation for the absence of type II supernovae from Ir galaxies. The clue lies in the marked disparity between galactic material and Magellanic Cloud material in chemical composition.

Shkloveskii's predictions on SN1987A

It is the lack of comparatively dense extended envelopes around the massive stars in the Magellanic Clouds due to the weakness of the stellar wind which, in my view, accounts for the absence of type II supernova there. According to the analysis by Grasberg et al.,[6] when the core of a fairly massive star explodes and instantaneously liberates energy, the star has to be embedded in a rather extended (radius R > 1 AU) envelope in order for a type II supernova phenomenon to be observed. Otherwise the luminosity at maximum light will be a hundred times below that of typical SN II events, and the brief maximum will last only a few tens of minutes.

We therefore conclude that type II supernova outbursts may fall to be observed in Ir galaxies for the same reason that the Cassiopeia A explosion produced no optical effect.[7] In our Galaxy, however, massive-star outbursts of this kind are probably an exception,[1)] while in irregular galaxies the lack of an extended envelope around the star when its core explodes is the general rule.

Четыре исхода для массивных звёзд – S.Woosley

With some uncertainty about exact demarcations, one can delineate four kinds of deaths for non-rotating helium stars. (For rotation decrease main sequence mass 10 - 20%)

He Core	Main Seq. Mass	Supernova Mechanism
$2 \le M \le 40$	$10 \le M \le 95$	Fe core collapse to neutron star or a black hole
$40 \le M \le 60$	$95 \le M \le 130$	Pulsational pair instability followed by Fe core collapse
$60 \le M \le 137$	$130 \le M \le 260$	Pair instability supernova
$M \ge 137$	$M \ge 260$	Black hole. Possible GRB

Для света нужна высокая удельная энтропия

Грубо оценим энтропию на барион при взрыве C/O белого карлика ($\rho = 3 \cdot 10^9$ г/см^3, $T = 10^{10}$ K) и сравним с энтропией реликтового излучения в современной вселенной.
Можно взять формулы:
$n = N/V$, $P = nT$ и $E_{\rm th} = (3/2)PV = (3/2)NT$, – удобно измерять температуру в единицах энергии, – так что (μ – это химпотенциал):

$$NA_iST = \frac{5}{2}NT - N\mu,$$

откуда энтропия в классическом газе с массой ионов $m_i = A_i m_p$

$$A_iS = \frac{5}{2} - \ln\left[\frac{n_i}{g_i}\left(\frac{2\pi\hbar^2}{m_iT}\right)^{3/2}\right].$$

Это формула Сакура-Тетроде (Sackur-Tetrode), а энтропия S здесь безрамерна и дана на барион. Возьмём углерод, $A_i = 12$ и подставим заданные T и $\rho = m_i n_i$ с переводом в нужные единицы. Получим (положив $g_i = 1$, всё равно он под логарифмом) S немного больше единицы. Фотоны дают по формуле $S \approx n_\gamma/n_{\rm baryon}$ число меньше единицы, а электроны ещё меньше, так как их химпотенциал велик, пар нет. Итак, при $T \sim 10^{10}$ K белый карлик по энтропии в миллиарды раз холоднее, чем вселенная при трёхградусном излучении.

SN light

Many photons $\Rightarrow$ high entropy: $S \sim n_\gamma / n_b$.
At $T \sim 3$ K we live in a HOT Universe at high S.
At $T \sim 10^{10}$ K a White Dwarf exploding as a thermonuclear SNIa is not so hot!
It is COLD.

Entropy source needed

At $R \sim 10^8$ cm we have $T \sim 10^{10}$ K.
Для адиабаты:

$$P \propto \rho^\gamma, \qquad T \propto \rho^{\gamma-1}.$$

Имеем плотность $\rho \propto 1/R^3$.

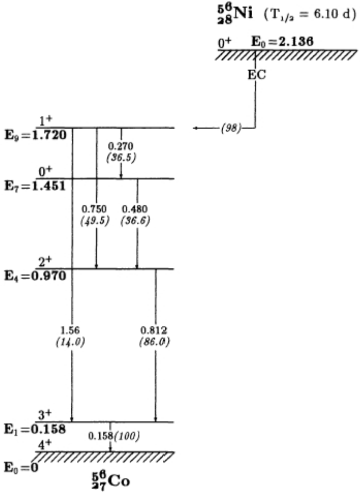
If we had $\gamma = 4/3$, then at $R \sim 10^{15}$ cm we would get $T \propto 1/R \sim 10^3$ K – already too cold to shine.

But in reality γ is close to $5/3$ since radiation does not dominate, a bit less due to recombination, and we have $T \propto 1/R^2$ – like CMB temperature!

Thus a source of S is needed for luminous SNe: either radioactivity or shocks.

Sources of entropy in SN I and SN1987A

radioactive decays $^{56}Ni \rightarrow {}^{56}Co$ (following D.Nadyozhin)



Sources of entropy in SN II: Shocks

Shock inside the star remains in adiabatic phase while optical depth,

$$\frac{\delta R}{l} > \frac{c}{D},$$

where δR is the distance from the shock to the photosphere (Ohyama N. 1963, also Morozov Yu.I. 1966)
When

$$\frac{\delta R}{l} \lesssim \frac{c}{D},$$

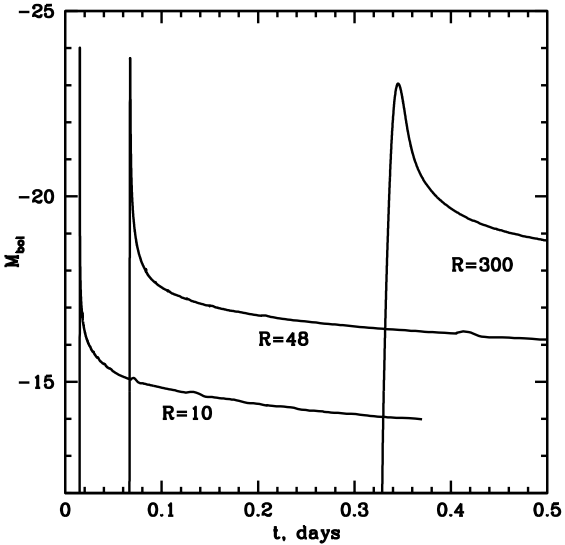
the burst of photon luminosity begins: shock break-out. The shock is highly non-adiabatic then and a density peak is built up similar to the old SNRs.

Вспышка при выходе УВ на поверхность предсверхновых типа II

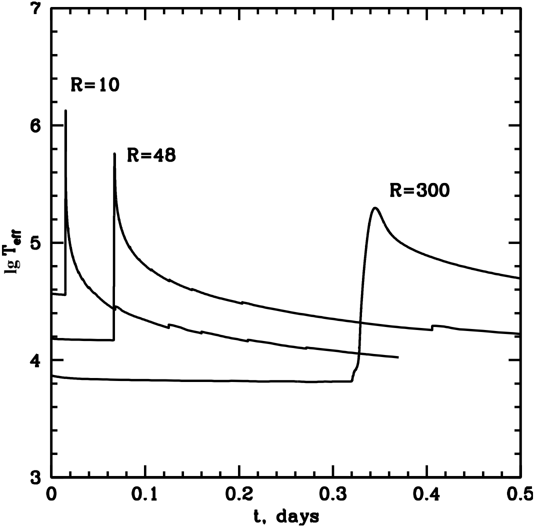
Впервые задача о выходе ударной волны по спадающей плотности $\rho \propto (\delta R)^n$ была поставлена Гандельманом и Франк-Каменецким (1956) – автомодельные решения, также Сакураи (1960), Грасберг (1981). В компактных предсверхновых возможно ускорение до релятивистских скоростей и вспышка рентгеновского излучения.
Раньше думали что даже гамма излучение возможно Colgate (1974), Бисноватый-Коган и др. (1975) – модели гамма-всплесков. Эти надежды не вполне оправдались — излучение слишком мягкое (Weaver 1976).

Shock Luminosity in SN II

Shocks: Different radii at shock-breakout epoch



Effective Temperature in SN II

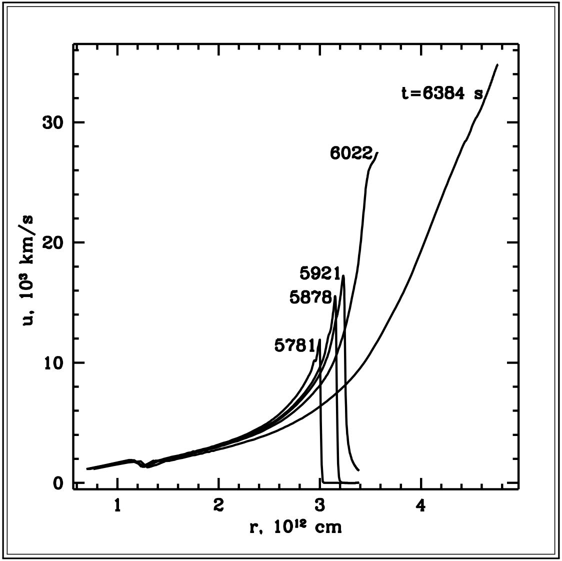


Computing shock-breakout

When the shock approaches surface, where the density of matter ρ falls as $\rho \propto (\delta R)^n$, velocity grows in agreement with the self-similar solution by Gandel'man and Frank-Kamenetskii (1956), Sakurai (1960).

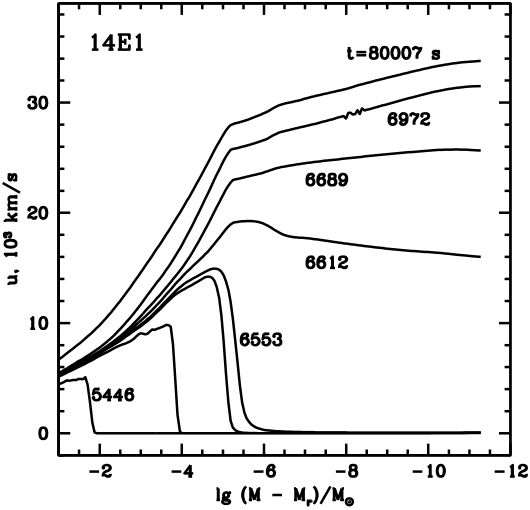
In the outermost layers (with Thompson optical depth $\tau \sim c/D \approx 10$ and less, where D is the shock velocity) the radiative losses become significant and shock acceleration ends.

Velocity, Eulerian



Shocks inside SNe, e.g., SN 1987A

velocity *vs* mass from surface, time in seconds is given

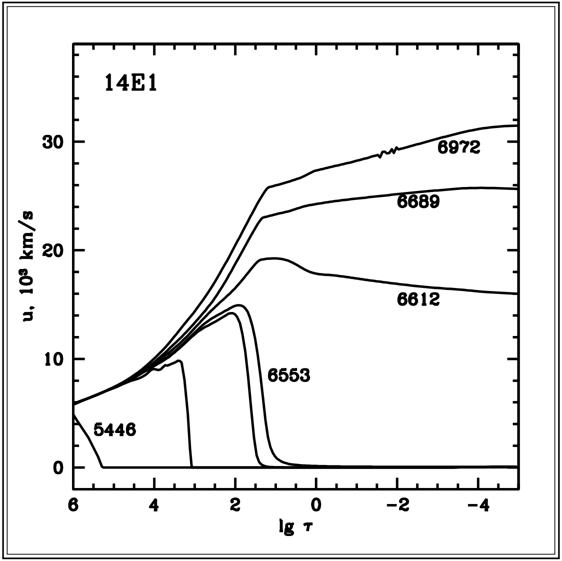


End of shock acceleration

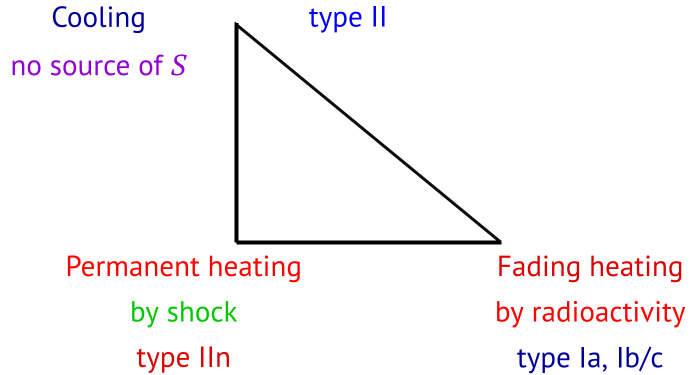
The termination of the shock acceleration process is clearly observed in computations.

Next figure shows the profiles of velocity as a function of optical depth τ (Blinnikov 1999). Just at $\tau \sim c/D \sim 10$, as predicted, the photons start 'running-out' from behind the shock front. These photons slightly accelerate the outer layers, however, the cumulation of energy on the small mass is already not efficient due to strong radiative losses.

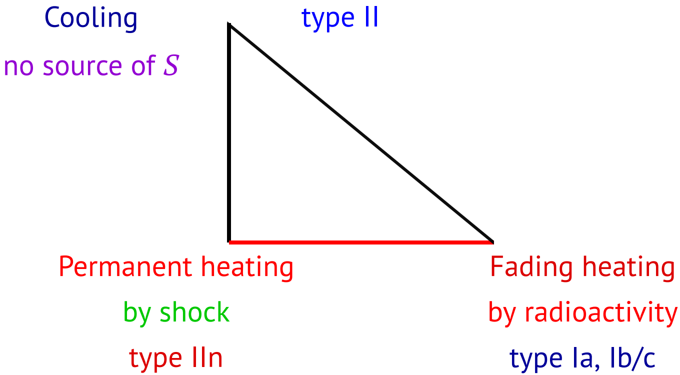
Velocity – optical depth



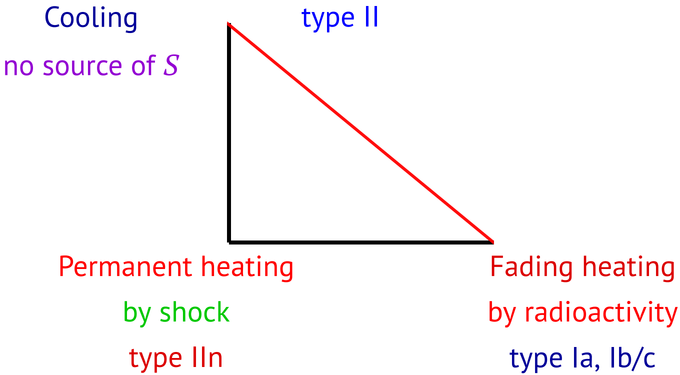
SN Light Source



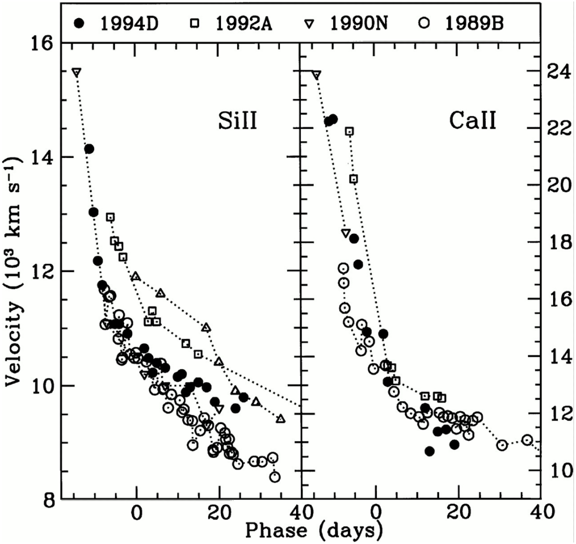
SN Light Source



SN Light Source



Скорости из спектров



Из ширины спектральных линий получается скорость в атмосфере до $\mathbf{v} \sim \mathbf{10^4}$ км/с и выше (кроме SN IIn, где скорость на порядок меньше).
Из кривых блеска – масса $\mathbf{M}_{\rm ej} \sim 1\,M_\odot$ до десятков $M_\odot$.
Отсюда энергия
$\mathbf{E} \sim M_{\rm ej}v^2/2 \sim 10^{51}$ ergs $\equiv 1$ foe $\equiv 1$ Бете

Кинетическая энергия выброса сверхновых

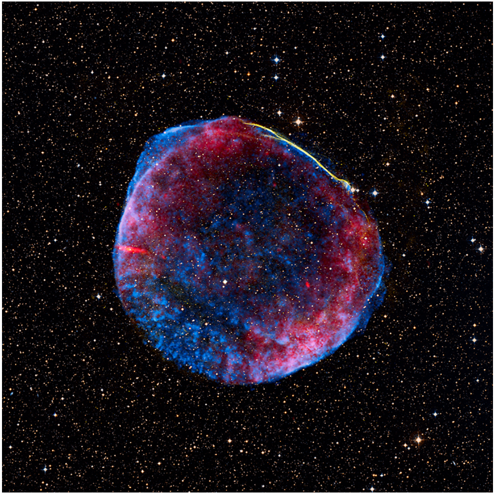
имеет характерное значение для всех типов
$E \sim 10^{51}$ эрг $\equiv 1$ foe
(из 10 в степени 51 = Fifty One Ergs),
хотя известны и отклонения примерно на порядок вверх и вниз от этого среднего.

Эта энергия диссипирует в межзвездной среде, нагревает ее, порождает рентгеновское излучение и космические лучи.

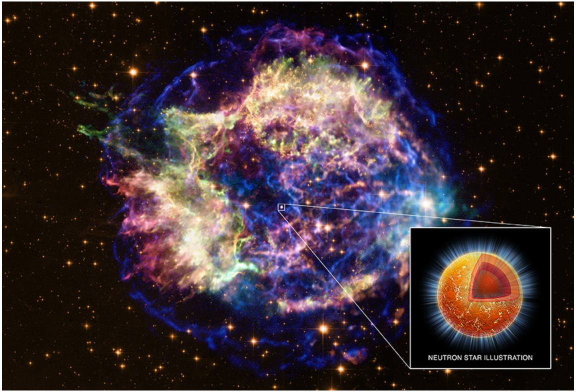
Выброс обогащает среду тяжелыми элементами. Ударные волны сгребают вещество и это приводит к рождению молодых звезд.

Остатки сверхновых – Supernova Remnants, SNRs

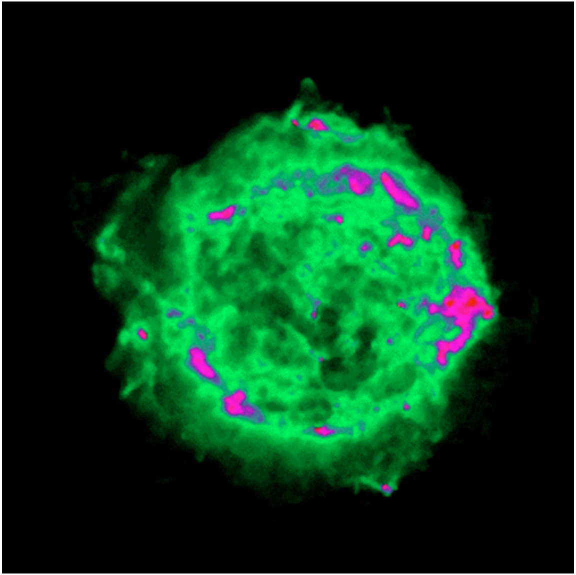
SNR 1006



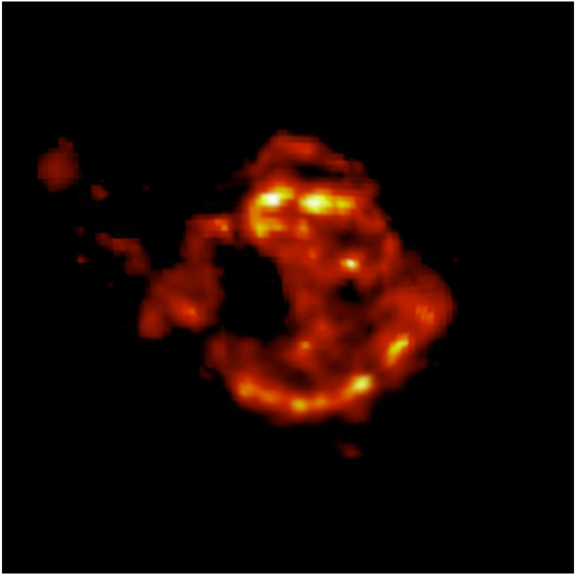
Supernova Remnant (SNR) Cas A: Chandra X-ray observatory



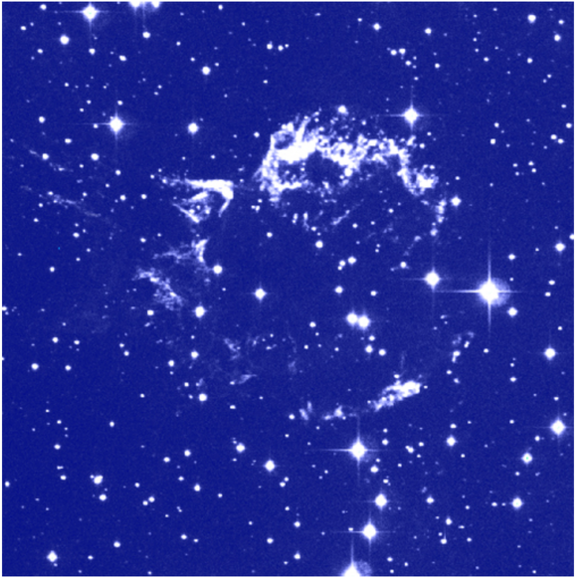
SNR Cassiopeia A Radio



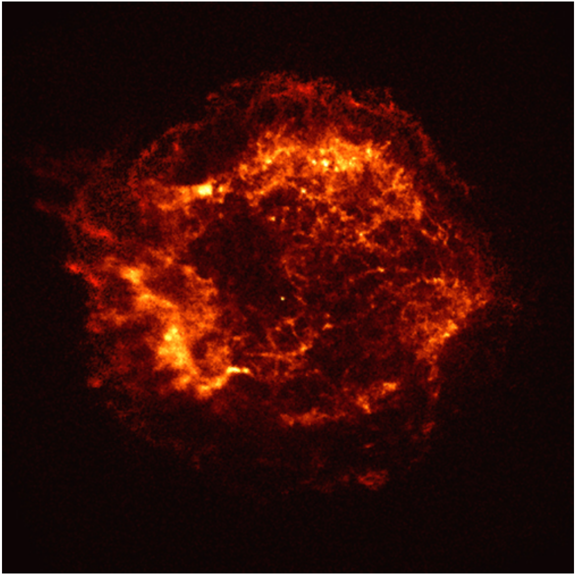
SNR Cas A Infrared



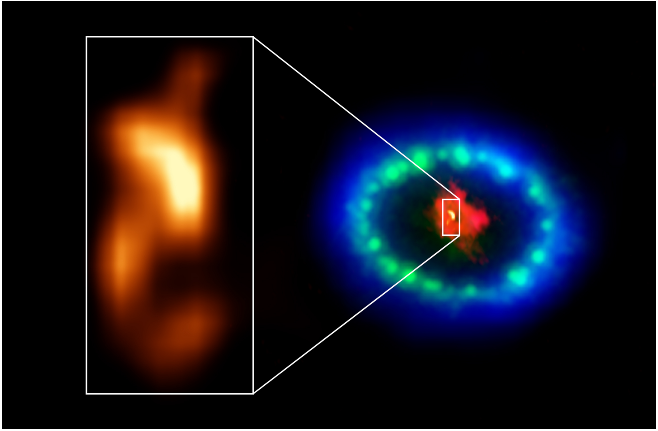
SNR Cas A visible light



SNR Cas A X-ray



SNR 1987A



ALMA (красн., радио): пыль и хол.газ + Chandra X-ray (голуб.) + HST (зелён., видимый свет).

Важные числа о сверхновых:

Кинетическая энергия выброса $\sim 10^{51}$ эрг = 1 **foe**

У обычных SN световая энергия за первый год ~ 0.01 foe

У сверхмощных SLSNe: ~ 1 foe и выше

Для SN 1987A: $E_{\rm kin} = (1 - 1.5)$ foe (Имшенник+Попов 1992, Блинников 1999, Утробин 2005)
Масса $(14 - 19) M_{\odot}$.
Радиус предсверхновой $(47 - 50) R_{\odot}$.
Более новые результаты - ниже.

A. Menon et al. 2018: binary progenitor

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **482,** 438–452 (2019) doi:10.1093/mnras/sty2647
Advance Access publication 2018 October 3

Explosions of blue supergiants from binary mergers for SN 1987A

Athira Menon,[1★] Victor Utrobin[2,3★] and Alexander Heger[1,4★]

Based on the work of Menon & Heger, we present the bolometric light curves and spectra of the explosions of blue supergiant progenitors from binary mergers. We study SN 1987A and two other peculiar Type IIP supernovae: SN 1998A and SN 2006V. The progenitor models were produced using the stellar evolution code KEPLER and then exploded using the 1D radiation hydrodynamic code CRAB. The explosions of binary merger models exhibit an overall better fit to the light curve of SN 1987A than previous single star models because of their lower helium-core masses, larger envelope masses, and smaller radii. The merger model that best matches the observational constraints of the progenitor of SN 1987A and the light curve is a model with a radius of 37 $R_\odot$, an ejecta mass of 20.6 $M_\odot$, an explosion energy of 1.7×10^{51} erg, a nickel mass of 0.073 $M_\odot$, and a nickel mixing velocity of 3000 km s^{-1}. This model also works for SN 1998A and is comparable with earlier estimates from semi-analytic models. In the case of

Xiang et al. 2023

SN 2018hna: Adding a Piece to the Puzzles of the Explosion of Blue Supergiants

Danfeng Xiang,[1★] Xiaofeng Wang,[1,2,3†] Xinghan Zhang,[1] Hanna Sai,[1] Jujia Zhang,[4] Thomas G. Brink,[5] Alexei V. Filippenko,[5] Jun Mo,[1] Tianmeng Zhang,[6,7] Zhihao Chen,[1] Luc Dessart,[8] Zhitong Li,[9,7] Shengyu Yan,[1] Sergei I. Blinnikov,[10,11] Liming Rui,[1] E. Baron[12] and J. M. DerKacy[13,12]

Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 2, pp.2965-2982
April 2023

SN2018hna: фотосферные скорости

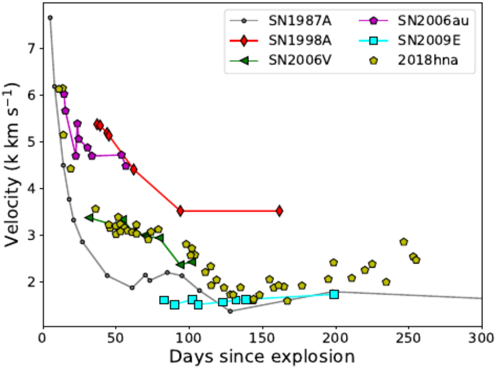


Figure 7. Fe II line velocities of SN 2018hna in comparison with several other 87A-like SNe.

SN2018hna: кривые блеска

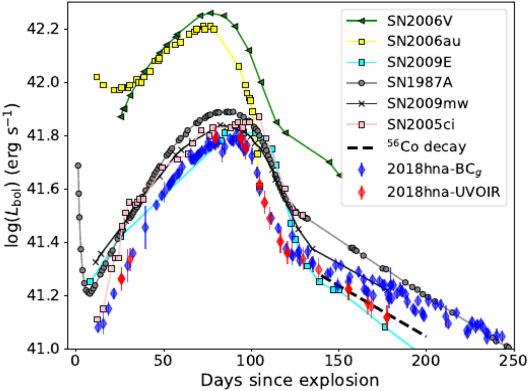


Figure 11. Bolometric light curve of SN 2018hna compared with that of other 87A-like SNe II. The red diamonds represent the bolometric light curve of SN 2018hna established with the UVOIR light curves, while the blue diamonds indicate the one derived from the ZTF gr-band light curves with bolometric corrections (see text for details). The black dashed line shows a ^{56}Ni -powered light curve with $M_{\rm Ni} = 0.05\ M_{\odot}$.

STELLA и анализ небулярных линий

Предсверхновая SN2018hna по нашим моделям имела радиус $\sim 45R_{\odot}$ (т.е. была голубым сверхгигантом), массу выброса $(13.7 - 17.7)M_{\odot}$, а кинетическую энергию (1.0-1.2) foe.
Из небулярных линий [OI] получается оценка массы кислорода $(0.44 - 0.73)M_{\odot}$, тогда на главной последовательности масса предсверхновой была $< 16M_{\odot}$.

Более экстремальные события

A&A 532, A100 (2011)
DOI: 10.1051/0004-6361/201117137

Astronomy & Astrophysics

Supernova 2000cb: high-energy version of SN 1987A

V. P. Utrobin[1,2] and N. N. Chugai[3]

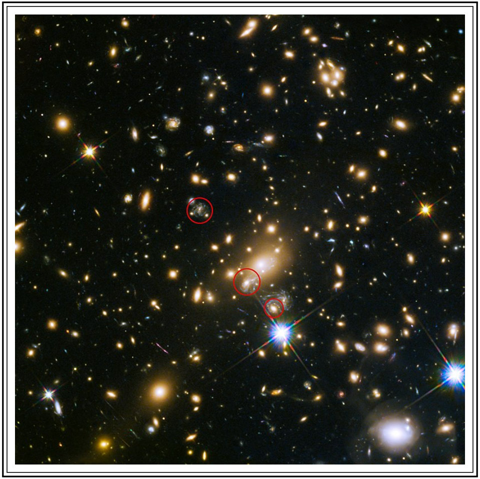
Results. We constructed the hydrodynamic model by fitting the photometric and spectroscopic observations. We infer a presupernova radius of $35 \pm 14\ R_\odot$, an ejecta mass of $22.3 \pm 1\ M_\odot$, an explosion energy of $(4.4 \pm 0.3) \times 10^{51}$ erg, and a radioactive ^{56}Ni mass of $0.083 \pm 0.039\ M_\odot$. The estimated progenitor mass on the main sequence lies in the range of $24-28\ M_\odot$. The early Hα profile on Day 7 is consistent with the density distribution found from hydrodynamic modeling, while the Hα line on Day 40 indicates an extended ^{56}Ni mixing up to a velocity of 8400 km s^{-1}. We emphasize that the dome-like light curves of both supernova 2000cb and supernova 1987A are entirely powered by radioactive decay. This is unlike normal type IIP supernovae, the plateau of which is dominated by the internal energy deposited after the shock wave propagation through the presupernova. We find signatures of the explosion asymmetry in the photospheric and nebular spectra.
Conclusions. The explosion energy of supernova 2000cb is higher by a factor of three compared to supernova 1987A, which poses a serious problem for explosion mechanisms of type IIP supernovae.

Тёмная материя: наблюдательные свидетельства

- Образование крупномасштабной структуры Вселенной
- Избыток массы во внешних частях галактик (кривые вращения галактик)
- Избыток массы в скоплениях галактик (по дисперсии скоростей галактик, по горячему газу и по массе гравитационных линз)
- Реликтовый фон: $\Omega_m \sim 0.27$, но $\Omega_{bar} \sim 0.04$

Можно ли модифицировать гравитацию и обойтись без DM?

Попытки есть, но ...



The Astrophysical Journal, 907:35 (15pp), 2021 January 20 https://doi.org/10.3847/1538-4357/abcd98

Strongly Lensed Supernova Refsdal: Refining Time Delays Based on the Supernova Explosion Models

Petr Baklanov[1,2,3], Natalia Lyskova[2,4], Sergei Blinnikov[1,5], and Ken'ichi Nomoto[5]
[1] NRC "Kurchatov Institute" - ITEP 117218 Moscow, Russia; petr.baklanov@itep.ru
[2] Space Research Institute (IKI), Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia
[3] National Research Nuclear University MEPhI, Kashirskoe sh. 31, Moscow 115409, Russia
[4] P.N. Lebedev Physical Institute, Leninskiy prospect 53, Moscow 119991, Russia
[5] Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
Received 2020 July 4; revised 2020 November 19; accepted 2020 November 23; published 2021 January 25

Abstract

We explore the properties of supernova (SN) "Refsdal"—the first discovered gravitationally lensed SN with multiple images. A large magnification provided by the galactic-scale lens, augmented by the cluster lens, gave us a unique opportunity to perform a detailed modeling of a distant SN at $z \simeq 1.5$. We present results of radiation hydrodynamics modeling of SN Refsdal. According to our calculations, the SN Refsdal progenitor is likely to be a more massive and energetic version of SN 1987A, i.e., a blue supergiant star with the following parameters: the progenitor radius $R_0 = (50 \pm 1) R_\odot$, the total mass $M_{\rm tot} = (25 \pm 2) M_\odot$, the radioactive ^{56}Ni mass $M_{^{56}\rm Ni} = (0.26 \pm 0.05)\, M_\odot$, and the total energy release $E_{\rm burst} = (4.7 \pm 0.8) \times 10^{51}$ erg. Reconstruction of SN light curves allowed us to obtain time delays and magnifications for the images S2–S4 relative to S1 with higher accuracy than previous template-based

Важно для космологии!

The Astrophysical Journal, 948:93 (33pp), 2023 May 10 https://doi.org/10.3847/1538-4357/ac4ccb

The Magnificent Five Images of Supernova Refsdal: Time Delay and Magnification Measurements

Patrick L. Kelly[1], Steven Rodney[2], Tommaso Treu[3], Simon Birrer[4], Vivien Bonvin[5], Luc Dessart[6], Ryan J. Foley[7], Alexei V. Filippenko[8,9], Daniel Gilman[3,10], Saurabh Jha[11], Jens Hjorth[12], Kaisey Mandel[13,14], Martin Millon[5], Justin Pierel[2], Stephen Thorp[13], Adi Zitrin[15], Tom Broadhurst[16], Wenlei Chen[1], Jose M. Diego[17], Alan Dressler[18], Or Graur[19,20], Mathilde Jauzac[21,22,23], Matthew A. Malkan[3], Curtis McCully[24,25], Masamune Oguri[26,27,28], Marc Postman[29], Kasper Borello Schmidt[30], Keren Sharon[31], Brad E. Tucker[32,33,34], Anja von der Linden[35], and Joachim Wambsganss[36,37]

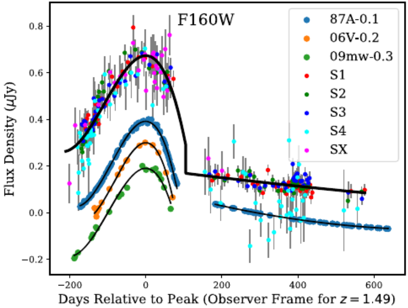


Figure 3. The observer-frame ($z = 1.49$) broadband light curves at 5000–7000 Å of SN Refsdal and those of low-redshift SN 1987A–like SNe with a similar shape stretched in time by a factor of 2.49. All light curves are well fit by a piecewise polynomial function. In the fits shown above, the

С опорой на Бакланова и др.

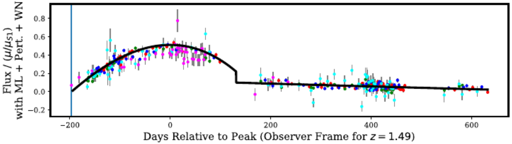


Figure 11. Components of a single set of simulated light curves of the five appearances of SN Refsdal. The top panel shows the perturbation applied to the fiducial piecewise polynomial model. The perturbation is a realization of a GP model of the residuals of the Baklanov et al. (2021) light curves from the best-fitting piecewise polynomial model. The next panel plots the change in apparent magnification in the F125W band due to microlensing by a randomly placed set of stars and stellar remnants. The middle panel plots the generative light-curve model without microlensing (ML) included. Motivated by fits to the light curves of low-redshift SN

Выводы

Знаменитая сверхновая SN1987A была очень слабой по абсолютной звёздной величине (как было предсказано И.С. Шкловским), но обладала обычной для сверхновых кинетической энергией взрыва около 1 foe=10^{51} эрг.

Наши радиационно-гидродинамические модели дают для SN Refsdal почти 5 foe.

Есть и другие примеры объектов того же пекулярного типа II как SN1987A, но с повышенной энергией взрыва.

В то же время предсверхновая SN2018hna по нашим моделям имела радиус $\sim 45 R_\odot$ (т.е. была голубым сверхгигантом), массу выброса $(13.7 - 17.7) M_\odot$, а кинетическую энергию (1.0-1.2) foe.

Из небулярных линий [OI] получается оценка массы кислорода $(0.44 - 0.73) M_\odot$, тогда на главной последовательности масса предсверхновой была $< 16 M_\odot$.

В обычной эволюции одиночных звёзд такие малые массы не доходят до коллапса на стадии голубого сверхгиганта. Так что скорее всего в этом случае, как и в SN1987A, была эволюция в двойной системе (возможно при меньших массах компонент).

Спасибо за внимание!