PROCEEDINGS OF SCIENCE

Mechanism of the SN Ia explosions

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Last 10 years observational data on the type Ia supernova rates are in excellent agreement with the earlier results of the population synthesis of binary stars and confirm that the overwhelming majority of type Ia supernovas ($\sim 99\%$) in elliptical galaxies form via mergers of binary white dwarfs with a total mass exceeding the Chandrasekhar limit. The very first evolutionary computations of such processes in elliptical galaxies (population synthesis) performed using the Scenario Machine in 1996 (Lipunov et al. [1]) and showed that the mechanism of white-dwarf merging outperforms accretion by two orders of magnitude already one billion years after the formation of the elliptical galaxy. A special class of type Ia supernovae, that is not subject to ordinary and additional intragalactic gray absorption and chemical evolution, has been identified. Analysis of the Hubble diagrams constructed for these supernovae confirms the accelerated expansion of the Universe irrespective of the chemical evolution and possible gray absorption in galaxies.

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1. Introduction

The interest in type Ia supernovae is caused with possibility to use them as standard candles for cosmology, based on a tight empirical relation between their peak luminosity and the width of their light curve, which led the researchers to suspect the presence of dark energy in the Universe ([2], [3]), triggered mass discovery of supernovae, resulting in an almost 50-fold increase of the number of these stars studied in the last decade. Luminosity distance measurements of Type Ia supernovae led to wide-ranging efforts trying to characterize its observational properties and understand its theoretical origin. Observed variations of SNe Ia peak luminosities can be explained as a function of metallicity, age, environment, morphological type of the supernovae hosts, but most of these variations can be calibrated, and corrected away, if the correlation between the peak luminosity and the rate of decline is taken into account ([4]): the scatter in distances is then much reduced. The problem arises with evolution, since these effects are not known a priori, and can influence to a cosmological constant. For the first time the magnetorotational mechanism for core-collapse SN explosions was suggested in 1970 by [5]. Also we need to take into account the role of strong magnetic fields as one of the SNIa mechanism [6].

The mass discovery of supernovae in recent years allowed the researchers to observe for the first time the dramatic evolution of the supernova rate in elliptical galaxies, which was predicted more than 10 years ago via population synthesis [7].

2. The mechanism of supernova Ia explosion in elliptical galaxies

Type Ia supernovae are now generally believed to be products of nuclear explosions of white dwarfs that have reached the Chandrasekhar limit (for a review see [8].

Their principal characteristic constraining models is their absence of hydrogen in their spectrum. They correspond to the total explosion of a carbon-oxygen white dwarf. They must accrete mass through binary evolution (since these WD are not massive enough at the beginning), and there are two possibilities: either two carbon-oxygen white dwarfs merge, in a time scale of a few 100 Myr, or only one carbon-oxygen white dwarf is accreting , with a longer time-scale, a few Gyrs, the most likely scenario.

No appreciable star formation goes on in elliptical galaxies. Only low-mass stars remain in these systems after the first billion years of their evolution. The evolution of all massive stars (with M > 8-10 $M\odot$) ends completely with the formation of neutron stars and black holes. Low-mass stars by themselves cannot produce supernova explosions, because their evolution ends with a soft formation of white dwarfs with masses below the stability limit (the Chandrasekhar limit). However, a delayed (by several billion years) accumulation of the Chandrasekhar mass may occur in binary systems - as a result of either the accretion of matter from a companion (the so-called SD-mechanism [9], or merger (the DD-mechanism [10] , [11]).

The very first evolutionary computations of such processes in elliptical galaxies (population synthesis) performed using a special computer code - the Scenario Machine ([1] and [12]) - showed by [7] that the mechanism of white-dwarf merger outperforms accretion by two orders of magnitude already one billion years after the formation of the elliptical galaxy (see Figure 1).

Thus the observed variation of the supernova rate in elliptical galaxies confirms not only the model of white-dwarf mergers as the main mechanism of type Ia supernovae explosions. However at early time ($\sim 10^8$ yrs) accretion mechanism is the main ([14]) and we predict a high soft X-ray luminosity from galaxies with this age.

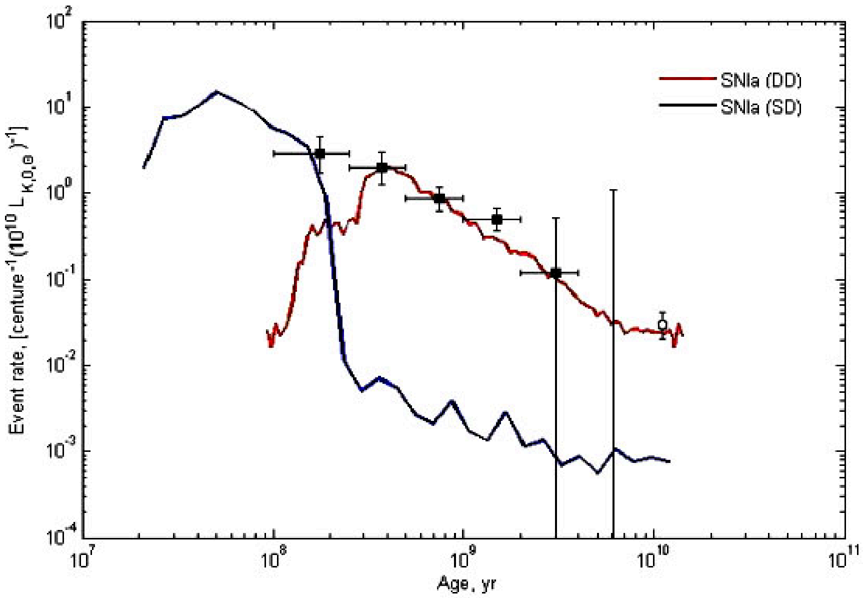

Figure 1: The SN Ia rate per century for a single starburst population whose total K-band luminosity is $10^{10}L_{K,\odot}$ at the age of 11 G yr $[centure^{-1}(10^{10}L_{K,0,\odot})^{-1}]$ (predicted by Jorgensen et al., 1997 [7]). The filled squares are the observational points[9]. The open circle is observational SN Ia rate in elliptical galaxies in the local Universe [15]

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3. "Pure" supernovae and accelerated expansion of the Universe

A remarkable feature of type Ia supernovae (SNe Ia) is the universality of their light curves and a constant absolute magnitude at maximum. This is explained by the similarity of the physical processes that lead to the outburst phenomenon. Generally, this is the thermonuclear explosion of a C-O white dwarf whose mass has become larger than the Chandrasekhar one as a result of accretion (Schatzmans mechanism) [9] or the merger of two white dwarfs with a total mass larger than the stability limit [10], [11]. Unfortunately, because of the differences in outburst mechanisms and differences in chemical composition and masses of the SN Ia progenitor stars, the observed light curves do differ between themselves. With the appearance of a large number of well studied supernovae, it has emerged that the absolute magnitude at maximum can change within 1m. Nevertheless, there are methods that allow the absolute magnitude of each SN Ia at maximum to be determined.

However, despite the present-day light-curve standardization m ethods, there are doubts in the validity of the "standard-candle" hypothesis. First, the so-called gray dust, whose absorption is wavelength independent and essentially cannot be taken into account [21], could lead to the dimming of distant supernovae. This can be large dust particles with typical sizes greater than $0.01\mu m$ [16]. In particular, the amount of such dust is proportional to the star formation rate, which increases into the past, and could produce the apparent fall in the power of distant supernovae. To explain the observed dimming of distant SNe Ia, [16], [17] invoked the intergalactic gray dust absorption mechanism. However, [20] ruled out this possibility. Furthermore, observations of distant quasars show that even if gray dust is present in intergalactic space, it cannot give absorption greater than 0.1m [19]. Gray dust inside host galaxies is a different matter. Its amount can also evolve with age, producing the apparent dimming of supernovae. Such dust is definitely present in galaxies ([18]).

The idea of our approach is to use only those supernovae that are at great distances from the host galaxy center. First, the oldest, metal-poor stars with an age comparable to that of the Universe lie at great distances from the nucleus (or high above the plane if we are dealing with an edge on spiral host galaxy). This automatically leads to a more homogeneous chemical composition of the progenitor stars. Second, SNe Ia far from the galaxy center most likely have a common explosion mechanism, namely the merger of white dwarfs. This is because there are no intermediate-mass stars in the galaxy haloes that could provide the accumulation of matter by white dwarf s in binary systems. Recall that the so-called Schatzman (or SD) mechanism [9] suggests the accumulation of mass by a white dwarf up to the Chandrasekhar limit in binary systems with a transfer rate of more than $10^8 - 10^{-7} M\odot/yr$.

In contrast, the white dwarf merger mechanism in elliptical galaxies provides up to 99% of SN Ia explosions [13]. Third, there is no dust in the galaxy haloes. For example, the thickness of the dust layer in our Galaxy does not exceed several kpc even at the edge (15-20 kpc). Of course, in elliptical galaxies dust is absent even deep inside the galaxy; besides, the age and, consequently, chemical composition of elliptical galaxies corresponds well to the first generation metal-poor stars. However,the point is that it is very difficult to determine the type of host galaxies for distant supernovae with a redshift of 1. Therefore, we considered only the supernovae far from the host galaxy center .

H_0 is taken to be 70 km/s/Mpc in the calculations. Since $\Omega_m + \Omega_\Lambda = 1$ in the suggested model, the only unknown parameter in the fitting procedure is Ω_Λ. The dark energy is chosen in such a way that the sum of the squares of the deviations of the observational points from the theoretical curve (3.1) is minimal. For clarity, we plotted he curve for $\Omega_\Lambda = 0$ on the same graph. We see that the slope of the Hubble diagram shows the presence of dark energy, accelerated expansion of the Universe, even for those supernovae that exploded in the regions where the absorption (including the gray one) is minimal! According to these data, the Universe is expanding with $\Omega = 0.66 \pm 0.18$ (see Figure 2).

We point out the paper by [22], who, based on completely different considerations, conclude that DD-process should be the dominating mechanism of type Ia supernova formation in elliptical galaxies. The above authors proceed from a simple logic that for the SD mechanism to operate, constant accretion is needed, which must be accompanied by soft X-ray flux, which, in turn, are found to be are smaller than predicted for the mechanism considered. However, first, the absence of something cannot be taken for positive evidence (as Ya.B.Zeldovich used to say, the fact that no electric wires have been found in excavation sites in Rome does not prove that ancient Romans had radio), and, second, it is not the accretion rate, but rather the integrated mass (over time) that

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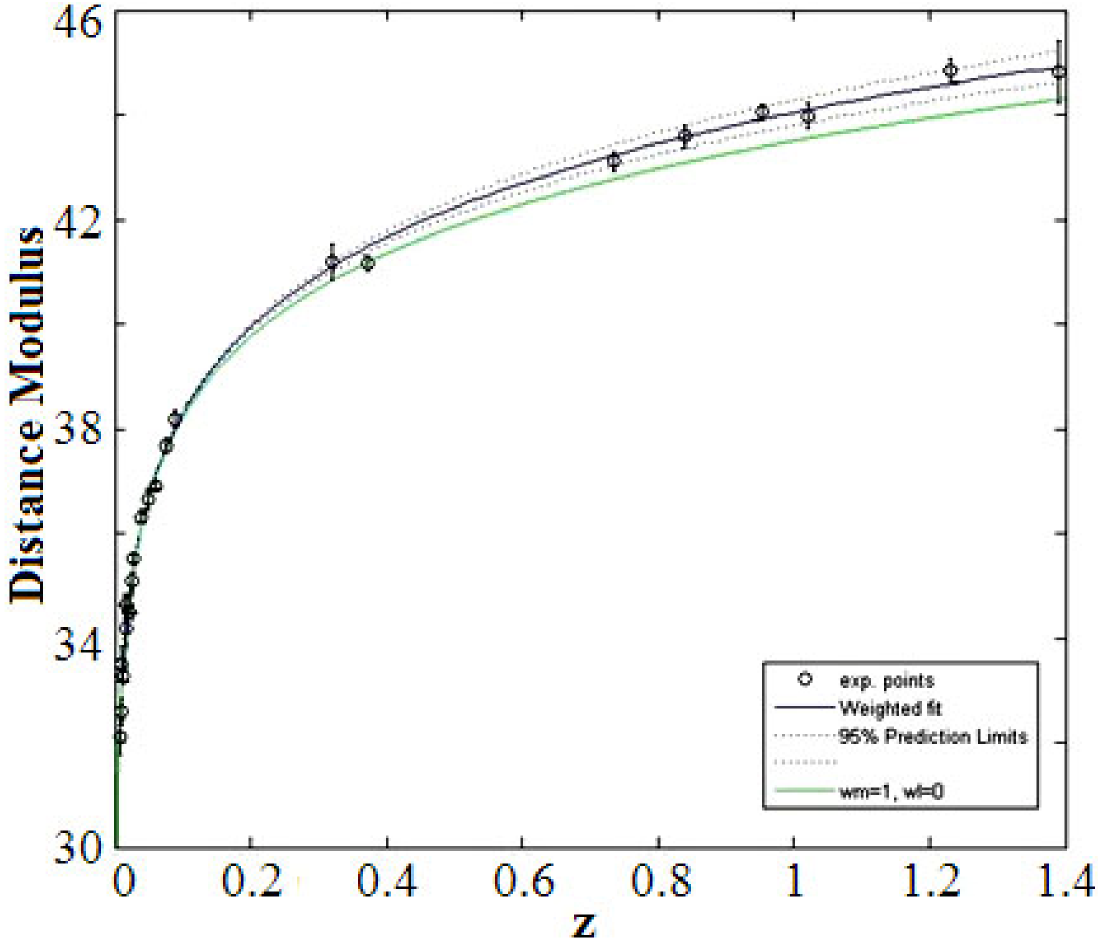

Figure 2: Hubble diagram for SNe Ia constructed from the points from the table. The red curve is the best fit to the observational data. The green curve corresponds to the Universe without dark energy. ([24])

is really important for the SD mechanism. Hence the X-ray luminosity should not be directly related to the supernova rate. In elliptical galaxies white dwarfs may grow their mass in systems of three types: (1) if a red- or yellow-dwarf secondary fills its Roche lobe (astronomers observe such systems as cataclysmic variables) or (2) if a helium secondary fills its Roche lobe (3) in wide systems where the white-dwarf's companion is a red giant (symbiotic stars).

4. Conclusion

SNe Ia play a great role in various areas of astrophysics. Studying them is very important for the problems of cosmology, because these objects have turned out to be excellent distance indicators in the Universe in view of their high luminosities and a remarkable similarity of their light curves. They also have shed light on the understanding of the chemical evolution of galaxies by explaining the presence of heavy elements in interstellar space. Nevertheless, the questions

PoS(MULTIF15)046

related to understanding the explosion physics and the nature of the processes that lead to the supernova phenomenon remain. As regards the "standard" nature of SNe Ia, here more and more questions arise with every year. Several SN Ia explosion mechanisms have been found to exist. The brightness of supernovae can change depending on the mechanism being realized. It is also quite possible that the SN Ia explosion can depend on the chemical composition of the progenitor star.

References

[1] Lipunov V. M., Postnov K. A., Prokhorov M. E., 1996, in Sunyaev R.A. ed., The Scenario Machine: Binary Populational Synthesis Review of Astrophysics and Space Physics, Vol. 17. Harwood Acad. Publ., Newark, NJ,p.1

[2] Riess A.G. et al., 1998, AJ 116, 1009.

[3] Perlmutter S. et al., 1999, AJ 517, 565

[4] Phillips M.1993, ApJ, 413, L105

[5] Bisnovaty-Kogan G. 1970 Astron.Zh., 47, 813

[6] Kundt W. 2008, NewAR, 52, 364

[7] Jorgensen H.E., Lipunov V.M., Panchenko I.E., Postnov K.A., Prokhorov M.E. 1997, ApJ,486,110

[8] Livio 2000 Type Ia Supernovae: Theory and Cosmology, eds. J.C. Niemeyer and J.W. Truran, Cambridge, Cambridge University Press, 33

[9] Whelan J., Iben I.Jr., 1973, ApJ 186, 1007

[10] Iben I.Jr., Tutukov A.V. 1984, ApJS, 54, 335

[11] Webbink R. 1984, ApJ,277, 355

[12] Lipunov V. M., Postnov K. A., Prokhorov M. E., Bogomazov A. I., 2009, Astron. Rep., 53, 91

[13] Lipunov V.M., Panchenko I.E., Pruzhinskaya M.V. 2011, New Astron., 16, 250

[14] Yungelson L.R. 2010, Astronomy Letters, 36, 780

[15] Mannucci F., et al. 2005, *A&A*, 433, 807

[16] Aguirre A. 1999, ApJ, 512, 19

[17] Aguirre A. 1999, ApJ, 525, 583

[18] Holwerda B.W. 2008, MNRAS, 386, 475

[19] Mortsell E., Goobar A. 2003, Journal of Cosmology and Astroparticle Physics, 09, 009

[20] Bassett B., Kunz M. 2004, Physical Review D69, 101305

[21] Bogomazov A., Tutukov A.V. 2011, Astron. Rep., 55, 497

[22] Gilfanov M., Borgan A. 2010 Nature, 463, p. 924

[23] Howell D.A. et al., 2001. ApJ, 556, 302

[24] Pruzhinskaya M., Gorbovskoy E., Lipunov V.M. 2011, Astronomy Letters, 37(10), 723

PoS(MULTIF15)046