Physics – Uspekhi **43** (5) 509 – 513 (2000)

PHYSICS OF OUR DAYS PACS numbers: **01.75.+m**, **01.90.+g**, 97.60.Bw, 98.58.Mj

Supernova explosions and historical chronology

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DOI: 10.1070/PU2000v043n05ABEH000753

Contents

Abstract. **Since ancient times (14th century BC), the so called 'new stars' and 'guest stars' — now known as supernova explosions, the strongest star explosions according to current views — have attracted the attention of man. The observed behavior of these stars was recorded most systematically in Chinese chronicles. In the present paper, age estimates for our galaxy's youngest (within the past millennium) supernova remnants are attempted using the simplest means of modern theoretical astrophysics. In most (five out of seven) cases such estimates are found to agree to within 100 years with their recorded dates, while in the two remaining cases a more elaborate analysis removes the significant differences obtained. The presence of pulsars in supernova remnants suggests alternative, independent approaches to supernova age estimation. The major conclusion is that the astrophysical determination of the age of the recorded supernova explosions confirms their historical chronology over the last 1200 years at least.**

1. Introduction

The unprecedented revision of the foundations of historical chronology that has been undertaken by a group of mathematicians headed by A T Fomenko (see, e.g., [1]) has aggravated the problem of the reliability of modern chronology. This creates an additional need for arguments from the natural sciences to be applied to establish the temporal coordinates of some notable ancient astronomical events. In what follows we shall briefly analyze the supernova explosions that were registered in some way in written documents over the last almost three millennia. For brevity we shall refer to them as recorded supernovae.

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Received 22 March 2000
Uspekhi Fizicheskikh Nauk **170** (5) 553 – 558 (2000)
Translated by K A Postnov; edited by M S Aksent'eva

Here first of all we should mention the astronomical analysis of the time of compilation of the first stellar catalog Ptolemy's *Almagest* that was performed by Yu N Efremov and Yu A Zavenyagin [2], who very convincingly determined this time to be the Ist century AD, which coincides with the conventional historical chronology. This analysis used the modern astronomical characteristics of the proper motions [1] of all the stars from the *Almagest* as the starting parameters. Below we shall use a similar approach, but applied to modern astrophysical studies of recorded supernova remnants.

Most of the recorded supernova explosions were registered by ancient Chinese astronomers, starting with records on bone plates made of turtle shells, which have survived to this day. Modern Chinese astronomers and astrophysicists possess extremely valuable information from such records, which they have successfully deciphered. This was demonstrated at the 145th Colloquium of the International Astronomical Union "Supernovae and Supernova Remnants", which took place in the ancient Chinese capital Xian on May 24 – 29, 1993 [3].

Of course, most of the scientific data on explosions of recorded supernovae within our Galaxy, i.e. relatively close to Earth, were already known in the literature, for example, in the beautiful popular book by I S Shklovskiĭ *Stars: their birth, life, and death* [4] and the deep monograph by T A Lozinskaya *Supernova stars and stellar wind. Interaction with galactic gas* [5]. Below we shall use the data from these books to determine theoretically the age of some supernova remnants identified with recorded supernova explosions. In addition to books [4, 5], we use materials of the 145 IAU Colloquium collected in the paper by Z Wang [6], a famous Chinese astrophysicist, who was a co-editor of the Colloquium Proceedings [3].

The supernova remnants of interest here have been thoroughly studied using various astronomical observations so that their main astrophysical characteristics are well known. To estimate the age of each of the remnants from the observations, the distance to the remnant D, its angular size φ, and the characteristic velocity of expansion V_{exp} should be known.

[1] In astronomical terminology, the proper motion is determined by the visual angular velocity of motion of stars perpendicular to the line of sight.

In addition, some supernova remnants contain pulsars which are rapidly rotating neutron stars with high magnetic field. To determine the characteristics age of a pulsar, its rotation period P and the rate of the period change with time (i.e. period derivative P') should be known. In additional, it is useful to have some knowledge of the state of the surrounding interstellar medium, in particular the spatial density distribution of matter $\rho_0(\mathbf{r})$.

The list of necessary and useful facts given above shows that we should be concerned with very modern observational data on supernova remnants, which however were obtained and collected over a rather broad time interval, say, over the entire second half of XXth century. This time interval must still be negligibly smaller than the age of supernova remnants under study. We note that the last explosion discovered by the naked eye (!) from Earth occurred about 400 years ago, more precisely, in 1604 AD.

Thus, using some of the modern astrophysical characteristics of the recorded supernova remnants (quantities D, φ, and V_{exp} determined above), we shall try to estimate the ages of these remnants, which can then be compared with their calendar ages. If the remnant contains a pulsar, it would be useful to independently evaluate its characteristics age from currently observed characteristics (values P and P' determined above).

2. Theoretical determination of supernova remnant ages

Very recently, starting from February 23, 1987, scientific ideas of supernova explosions have been greatly enriched by the explosion of supernova SN 1987A in the Large Magellanic Cloud [2], in the vicinity (!) of our Galaxy at a distance of 55 kpc (1 kpc $= 3.09 \times 10^{21}$ cm). This distance is still several times the typical size of our Galaxy (about 10 kpc). By the way, the SN 1987A explosion could be seen with the naked eye by people with good eyes in the southern hemisphere.

The SN 1987A has allowed us (the processing of observations is continuing at present) to significantly advance our theoretical understanding of the physics of supernova explosions, providing a wealth of observational data in a very broad range of the electromagnetic spectrum (from soft radio up to hard gamma-rays), and even ... on neutrino emission. Theoretical advances also concern the remnant of SN 1987A, which has been observed by astronomers for more than a decade.

To estimate the age of the remnant, we use below some basic and reliable results of the hydrodynamic theory of supernova remnants.

What is a supernova remnant from the physical point of view? Briefly speaking, it is the very rapidly expanding (even for cosmic scales) shell of the star that exploded as a supernova, which interacts hydrodynamically with the ambient interstellar medium, or simply rakes up or sweeps up the matter by a powerful shock wave produced after the explosion. The essence of this interaction is that after a relatively short stage of free expansion of the supernova shell, when one can fully neglect the external interstellar medium, the so called adiabatic stage of the expansion starts. At that stage complicated processes of loss and transfer of energy by the electromagnetic radiation within the remnant are unimportant, but hydrodynamic braking of the shell already occurs.

The stage of adiabatic expansion of the supernova remnant can be described sufficiently accurately by the famous solution of the problem of strong explosion first obtained by L I Sedov [7]. One of the relevant formulas of this solution looks very elementary:

$$t_{\mathrm{a}} = \frac{2}{5}\,\frac{R}{V_{\mathrm{exp}}}\,, \qquad (1)$$

where the age of the remnant t_{a} is expressed as the ratio of the spatial radius of the shell R, where $R = 0.5D\varphi$ (see the definition of D and φ above), and the characteristic expansion velocity of the remnant V_{exp} at the same time.

Note that the important role of expression (1) in the evaluation of the remnant's age was first stressed by I S Shklovskiĭ (see [4], p. 214). According to the theory [7], the remnant at the stage of adiabatic expansion represents a spherically symmetric volume with radius R bounded by a shock front moving with the speed V_{exp}. Most of the matter inside this sphere is the interstellar matter swept up, compressed, and heated by the shock wave after the explosion. Of course, at the center of the sphere there is a small portion of matter — the expanding shell of the supernova itself.

Clearly, at the early stage of free expansion formula (1) should read as $t_{\mathrm{f}} = R/V_{\mathrm{exp}}$. The numerical coefficient '2/5' in expression (1) accounts for the real effect of hydrodynamic braking of the remnant expansion (the velocity V_{exp} is 2.5 times smaller than the ratio R/t_{a}). One can check that the adiabatic stage of the remnant expansion (with the corresponding relationship $R \propto t^{2/5}$) indeed occurs under the physical conditions in the Galaxy at the age of several hundred years [8]. It is remarkable that formula (1) remains valid in such complicated physical conditions, where various processes of dissociation and ionization of interstellar atoms and molecules take place.

Consider now seven historically documented supernova explosions. In chronological order, these are: SN 837, SN 1006, SN 1054, SN 1181, SN 1408, SN 1572, SN 1604 (note that in their designation no conventional letter index is added). We shall refer to the historical calendar year of the supernova explosions as t_*.

Recorded supernovae are very rare events in the Galaxy separated by tens and even (more often) hundreds years. In historical records there is some evidence of earlier supernova explosions, but the characteristics of their remnants are insufficiently known for modern astronomy to use equation (1). We recall that the 'teaching of Fomenko' casts in doubt the historical chronology up to the beginning of the XVIth century, so all the supernova explosions we consider fall within this 'doubtful' period of 'History' [1].

So, let us find from equation (1) ages t_{a} of the historical supernovae listed above using the observational data on the values of $R = 0.5D\varphi$ and V_{exp} from the book of T A Lozinskaya [5], the paper by Z Wang [6], and also from the very recent paper by J Hughes [9] (the latter was used only for SN 1604). All these data and the ages of the remnants t_{a} derived from them are collected in the Table below. For comparison with the calculated ages t_{a}, the Table contains the calendar ages of the supernovae t_{SN} calculated from the modern chronology in the papers cited above and using our definition for t_*: $t_{\mathrm{SN}} = 1986 - t_*$ [5], $t_{\mathrm{SN}} = 1993 - t_*$ [6], $t_{\mathrm{SN}} = 1997 - t_*$ [9].

[2] The usual notation of a supernova includes the abbreviation SN and historical calendar year supplied with a letter of Latin alphabet.

Let us briefly discuss the results presented in the Table. First of all it is clear that the accuracy of the observed parameters is not very high, which is obviously the result of their measurement errors. Distances to the remnants are derived from observations in a very complicated way and their values have been continuously discussed. We quote distances D precisely as they are in the source papers. The angular sizes of the remnants φ are also rather uncertain since the remnants boundaries are blurred and their forms differ significantly from spherically symmetric. So the accuracy in determination of the remnant radius is in any case not better than that of the distance D.

X-ray observations, which have become possible over the last two-three decades, provide an important addition to observations of the supernova remnants in radio and optical wavelengths. Due to these observations we are able to include data on SN 837 and SN 1408 [6] in our Table, as well as precise data on SN 1604 [9].

Note also some features of the Table presented. Firstly, the second column contains not only the conventional astronomical notations of the supernova remnants, but also the 'names' of the most famous objects. Secondly, when quoting two sources (in the last column) the first citation refers to the columns containing values of D, φ, and R, and the second to $V_{\rm exp}$ and $t_{\rm SN}$ (values of $t_{\rm SN}$ are in brackets).

All the young supernova remnants from the Table, including recorded supernovae, can be subdivided into two major types [5]: shell-like remnants and the so-called 'plerions' (which means 'filled' in Greek). From the physical point of view, young supernova remnants differ in whether or not they contain a rapidly rotating neutron star, a pulsar, which is a source of relativistic electrons and magnetic fields in the case of 'plerion'. The outer edge of the shell-like remnants precisely coincides with the front of a strong shock wave. The energy released in the explosion is first almost completely transformed into the kinetic energy of the expanding shell of the star that has exploded as the supernova. Then the energy stored in the supernova remnant is gradually spent on the shock wave's propagation through the interstellar medium which is swept up and heated up in the wave.

Ideal hydrodynamics (which applies perfectly at the adiabatic stage of remnant evolution) predicts the highest matter density immediately behind the shock front, which propagates according to Sedov's solution of the strong explosion problem, i.e. by equation (1). Such a density distribution helps concentrate the remnant's own emission near the shock front despite some temperature increase toward the center.

The shell-like remnants include SN 837, SN 1006, SN 1572, and SN 1604. Their calculated ages ($t_{\rm a}$) are in good agreement (with an error less than ± 100 years) with the calendar age $t_{\rm SN}$ (see Section 4 for the case of SN 1604).

For 'plerions' SN 1054 and SN 1181 no agreement between calculated ($t_{\rm a}$) and calendar ($t_{\rm SN}$) ages has been found, especially for the most studied (!) Crab nebula. Generally, it is difficult to establish the location of the shock front for 'plerions', since practically no emission comes from the vicinity of the front [5]. The energy supplied by central pulsars also means that formula (1) becomes inapplicable to the real hydrodynamics of the remnant. The same is true for the remnant of SN 1408, although in that case the agreement between $t_{\rm a}$ and $t_{\rm SN}$ is fairly good (probably because of X-ray observations of the expansion velocity?).

Anyway, in the case of 'plerions' there is an independent means to estimate the age of the pulsar itself, which should be equal to the age of the supernova remnant because the rapidly rotating neutron star results from gravitational collapse practically simultaneously with the supernova explosion. The recent supernova explosion SN 1987A in the Large Magellanic Cloud, which provided us with a beautiful piece of evidence of the dramatic process of the simultaneous collapse and explosion, occurred practically in our neighborhood [10].

3. Theoretical determination of the characteristic ages of pulsars

In modern astrophysics the characteristic age of a pulsar $t_{\rm P}$ can be estimated from the following simple relationship obtained in the so-called dipole approximation (see, e.g., [6]):

$$t_{\rm P} = \frac{P^2 - P_0^2}{2PP'}\,, \tag{2}$$

where P and P' are the modern rotational period and the rate of period change (increase) of the radio pulsar, P_0 is the initial pulsar period, i.e. the one it had at birth in the supernova explosion. We emphasize that this period is the spin period of the neutron star and is usually very small (fractions of a second).

The pulsar age estimation from equation (2) would be elementary if a strong inequality $P \gg P_0$ held. Then the estimate $t_{\rm P} \approx P/2P'$ would be valid and quantities P and P' well known from observations — would allow to determine its characteristic age. For the remnant SN 1054 the parameters of its pulsar NP 0531 are well known: $P = 0.033$ s and $P' = 4.17 \times 10^{-13}$ s/s, where assuming $P_0 = 0$ we derive from

Table. Parameters of recorded supernovae.

Notation of the recorded supernova	Notation of the SN remnant from Catalog of galactic supernovae	D, kpc	φ, arcmin	R, pc	$V_{\rm exp}$, km/s	$t_{\rm a}$, years ($t_{\rm SN}$, years)	Reference
SH 837	G189.1 + 3.0; 3C157; IC443	1.5	40	9	3000	1170 (1156)	[6]
SH 1006	G327.6 + 14.6; PKS1459-41	1.2	30	5	2300	850 (980)	[5], table 5
SH 1054	G184.6−5.8; 3C144; Crab	2.0	6	1.75	1500	456 (932)	[5], table 6
SH 1181	G130.7 + 3.1; 3C58	2.6	8	3	1000	1170 (805)	[5], table 6
SH 1408	G69.0 + 2.7; CTB80	3.0	8	3.5	2000	684 (585)	[5], table 15; [6]
SH 1572	G120.1 + 1.4; 3C10; Tycho	3.0	3.6	3.3	3600	359 (414)	[5], table 5
SH 1604	G4.5 + 6.8; 3C358; Kepler	3.2	1.3	1.3	$\leqslant$ 300	1695 (382)	[5], table 5
SH 1604*	–"–	–"–	–"–	–"–	3040	418 (395)	[5], table 5; [9]

(2) $t_P = 1250$ years, which is not much higher than its historical age $t_{SN} = 932$ years.

It is interestingly to note that radio astronomy allows to be P and P' to be measured with an unprecedental precision, i.e. expressed by numbers with many significant figures. To get the exact pulsar age $t_P = t_{SN}$ from expression (2) with $t_{SN} = 932$ years and parameters P and P' for NP 0531 as given above, we should assume $P_0 = 0.017$ s. Note nevertheless that even for $P_0 = 0$ we evaluated the pulsar age in SN 1054 to a higher accuracy than in the Table. The situation is worse for the remnant SN 1181 since the pulsar is not seen by terrestrial observers, although its presence in the remnant ('plerion') is not in doubt [5].

The problem with the pulsar inside another 'plerion' SN 1048 has a different solution [6]. For a long time this remnant was thought to be an old one with an age of about 10^5 year. Such an age estimate would follow from equation (2) with $P_0 = 0$ using parameters $P = 0.0395$ s and $P' = 5.84 \times 10^{-15}$ s/s for the pulsar PSR 1951 + 32 located inside the remnant SN 1408. However, X-ray observations ultimately showed [6] that the remnant SN 1408 has a compact X-ray source in its center, most probably a rapidly rotating young neutron star which manifests itself in the radio band as the pulsar PSR 1951 + 32. According to (2) this is possible only if the initial pulsar period P_0 differs only insignificantly from the modern value $P_0 = 0.0394$ s [6].

It is important to note that the above value of P' (which is extremely small in comparison with that for NP 0531) is very typical for the known pulsar population, which now comprises many hundreds of pulsars. In contrast, the pulsar inside the remnant SN 1054 is anomalous for its rapid rotation braking and powerful energy supply to the remnant, which is responsible for the unique properties of the Crab nebula [4].

4. Features of the age determination of the SN 1604 remnant

The last two lines of the Table relating to the remnant SN 1604 needs explanation. Note from the very beginning that the inverted commas in the line for the SN 1604* remnant means the exact repetition of the values from the preceding line for the same SN 1604 remnant.

The characteristic expansion velocities of the youngest supernova remnant SN 1604 were found only from X-ray observations by the Einstein and ROSAT satellites. These data are much more accurate than previous estimate (three significant figures for V_{exp}) and are presented in the last line of the Table for SN 1604*.

Strictly speaking, we used a very accurate measurements of the relative expansion velocity of the remnant from paper [9]: $\alpha = 0.239$ percent per year (with respect to the remnant radius R). Incidentally, it is clear that such measurements can be used very successfully for age determination of a remnant since there is no need to know the distance D to the remnant. However, for uniformity in the Table we determined the equivalent quantity $V_{exp} = 0.01\alpha R/(3.16 \times 10^7)$ with the radius $R = 1.3$ pc, as in the previous line for SN 1604. This procedure yields exactly the same age† the remnant — as in the original paper [9] for $t_f = 418$ years, which confirms indirectly the old data [5] on the remnant radius.

It could seem excessive to discuss in such detail the procedure for determining the age of the remnant t_f, but we think it relevant because this demonstrates the prospects for a major improvement in the age determination of the recorded supernova remnants from X-ray observations which were not considered in J Hughes' paper [9].

It is easy to see that the age of SN 1604 ($t_f = 418$ years) is obtained from the relation

$$t_f = \frac{R}{V_{exp}}, \tag{3}$$

which is valid at the early stage of free expansion. It is for the youngest remnant SN 1604 that X-ray observations [9] proved that the stage of practically free expansion goes on for about 10 years, $R \propto t^m$ (where $m \approx 0.93$), and with account of this correction the calculated age of the remnant coincides with the recorded one with a minute difference of several years. The line before the last in the Table must obviously be rejected since it was based on erroneous estimate of the expansion velocity of the remnant $V_{exp} \leqslant 300$ km/s [5] and used formula (1) instead of (3).

5. Conclusions

We come to the following conclusions from the above considerations. The essentially approximate hydrodynamic theory of the evolution of supernova remnants can look more reliable if it is confirmed by detailed numerical calculations. These can consistently take into account such astrophysical quantities of interstellar matter as its inhomogeneous structure with some initial density distribution (even a multidimensional one), dissipative processes, excitation and ionization of molecules and atoms of the medium. Individual numerical hydrodynamic models can in principle be constructed for each particular supernova remnant without using the self-similar Sedov solution for the strong explosion problem, etc.

Moreover, such numerical models already partially exist, but they are beyond the scope of this paper. Our purpose was to demonstrate the significant coincidence between the calendar supernova ages and their remnant ages derived from modern astronomical observations using simple but scientifically approved methods. We are convinced that this aim has been achieved, since with an acceptable accuracy (an error of about ±100 years) these ages coincide. Thus the fantastic 'new chronology' of A T Fomenko et al., which distorts the historical chronology by many hundreds years [1], should be rejected.

Finally, we would like to bring an additional astronomical argument against the so called 'new chronology'. The identification of the Star of Bethlehem with the supernova explosion SN 1054, i.e. the new determination of the birth of Jesus Christ in 1054 AD [1], has absolutely no basis.

In fact, a much more convincing view is the well known one [3] that the Star of Bethlehem glow seen by our ancestors was due to a bright appearance of Halley's Comet, whose calculated period over the last 29 cycles is well established to be 76.1 years. Chinese records (see paper [6]) give evidence for the simultaneous appearance of the Halley's Comet and supernova SN 837 in 837 AD with an accuracy of literally

† About $t_f = R/V_{exp}$ see Section 2 after formulae (1). (Author's note to English edition.)

[3] Private communication by Yu N Efremov, whom the author specially thanks for this communication and useful discussions.

one month: a 'guest star' as SN 837 and a 'tailed star' as the Halley's Comet. Indeed, 11 orbital periods (10.997 periods) of the Halley's Comet around the Sun give almost exactly 837 years!

The renowned Byzantine historian L Diacon in his 'History' [11] systematically notes contemporary astronomical events, including the impressive comet appearance in 989 AD, the dramatic year in the history of the Byzantine Empire. It could clearly be the Halley's Comet again, exactly two periods after the Chinese sightings or exactly 13 periods (12.996 periods) after Jesus Christ Birth...

Of course, even our own epoch, when the Halley's Comet passed near the Sun in 1986, counts almost 26 periods (26.097 periods), but the extrapolation from the intermediate historical events discussed above is very important as evidence for the validity of the historical chronology over the vast time period from Jesus Christ Birth to our days. In addition, the Halley's Comet is not eternal, it demonstrates some evolutionary changes (in 1986 it frustrated astronomers not being bright enough) and its period cannot be a world constant...

I express my gratitude to V P Utrobin, who constructively supported my intention to write this note and brought the very recent paper by J Hughes to my attention, and to N A Vulikh for help in preparing the manuscript.

It is my pleasure to thank V I Kogan, V A Khrabrov, G N Zavenyagin, and historian-colleagues, first of all V I Kuzishchev. I also appreciate important critical notes made by L B Okun' after a careful reading of the manuscript.

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