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EVOLUTION OF THE RADIO LUMINOSITIES OF THE TYCHO AND KEPLER SUPERNOVAE REMNANTS

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Radio emission of historical supernovae remnants, Tycho (SNR1572) and Kepler (SNR1604) and evolution of their luminosity are considered. Measurement data of secular luminosity decrease rate, obtained earlier by the authors, were corrected with account of variation in time of the flux density of the reference sources. As a result, it is found that the SNR1604 luminosity at 1667 MHz is weakening with the annual mean rate equal to (0.2 ± 0.07)%. Similar rate for SNR1572 is (0.47 ± 0.05)%. Since the radio luminosity evolution, as well as energy densities of magnetic field and relativistic electrons inside SNR1604 and SNR1572 are essentially different, these remnants should be considered as different types of supernovae. Bandiera classified SN1604 as type SNIb or SNII.

Key words: *(stars:)supernovae - individual:Tycho and Kepler*

1. *Introduction.* Historical supernovae remnants in the Galaxy have ages between 300 and 1000 years, with their evolution during that period proceeding relatively quickly and within observational capabilities. Systematic study of these objects were initiated after 1960, when secular decay of their flux density was suggested by Shklovskii [1]. Radio astronomical observations have shown that, besides the predicted effect, luminosity and spectral shape of SNRs undergo nonstationary variations. Lately, neutron stars have been discovered in the shell-type supernova remnants, and although they are "radioquiet", the effect of neutron stars on SNR evolution is still unclear. Frequency variations of the spectrum may well be the consequence of the neutron star activity, and this effect is the subject for research. Below we describe the radio emission of historical supernovae remnants, Tycho (1572) and Kepler (1604).

2. *Secular decrease of SNR flux density.* Baade [2,3] has reconstructed the SN1572 and SN1604 light curves and attributed these supernovae to type I. Present values of the remnants parameters are given in Table 1.

The SNRs flux density variations are determined by comparison of measurement results obtained at different times. The SNR flux is usually referred to that of some calibration source assumed to be stable. However, recent observations of these reference sources have shown that their flux density is nonstationary, although sometimes very insignificantly. But this effect must be taken into account while studying the evolution characteristics of supernovae remnants.

Table 1

TYCHO AND KEPLER SUPERNOVAE PARAMETERS

Parameter	SN 1572		SN 1604	
External radius (arcsec)	216	[4]	100	[5]
External radius (pc)	3.34		2.18	
Distance (kpc)	3.2 ± 0.3	[6]	4.5 ± 1.0	[7]
Angular rate of expansion from filaments (arcsec/yr)	0.256 ± 0.026	[8]	0.005 ± 0.003	[9]
Parameter of expansion, $m (R \propto t^m)$	0.462 ± 0.024	[4]	0.65 ± 0.35	[5]
Altitude above Galaxy plane (pc)	72		533	[7]

The flux density ratio of SNR1572 (3C10), with two reference sources 3C123 and 3C147, was measured by us in October 1994, at a frequency 5000 MHz. The RT-70 radio telescope [10] was used. The results as compared with the 1967.4 similar measurements [11], are given in Table 2.

Table 2

TYCHO SNR TO 3C123 AND 3C147 FLUX DENSITY RATIOS IN TWO EPOCHS

Epoch	Flux density ratio	
	S_{3C10}/S_{3C123}	S_{3C10}/S_{3C147}
1994.8	1.155 ± 0.023	2.342 ± 0.047
1967.4	1.302 ± 0.027	2.598 ± 0.057

The annual mean rate of flux decline during the period 1967-1995 has been obtained from Table 2, and is equal to $(0.41 \pm 0.03)\%$ for SNR1572 (0.44% relative to 3C123 and 0.38% relative to 3C147) at a frequency 5000 MHz [12]. According to the VLA Calibrator Manual [13] during the same period the flux density decrease for the 3C147 reference source was 2.9%, and about 1% for 3C123 [14]. With account of this correction, the SNR1572 decay rate, relative to 3C123, should be taken as $(0.47 \pm 0.05)\%$ per year, and $(0.48 \pm 0.05)\%$ per year relative to 3C147. Similar observations at a frequency 960 MHz have been carried out by us in 1964 and 1987 with CygA source taken as a reference, which gave secular decrease rate $(0.47 \pm 0.13)\%$. Together with the present result, this means a steady flux density decay in the radio spectrum. Thus, the SNR luminosity has also decreased.

The secular flux density decrease for SNR1604 (3C358), equal to $(0.22 \pm 0.05)\%$ per year at 1667 MHz and $(0.27 \pm 0.1)\%$ per year at 5870 MHz, has been established between 1967.5 and 1987.5 [12]. RT-70 radio telescope was used, with 3C218 (Hydra A) taken as a reference source. The results are given in Table 3.

Table 3

KEPLER SNR1604 TO 3C218 FLUX DENSITY RATIOS AT TWO FREQUENCIES

Frequency, MHz	Flux density ratio	
	S_{3C358}/S_{3C218} (1987.5)	S_{3C358}/S_{3C218} (1967.5)
1667	0.379 ± 0.002	0.396 ± 0.002
5870	0.539 ± 0.008	0.569 ± 0.004

The flux density ratios for SNR1604 and Hydra A in 1967 were calculated using the measurement data in the frequency range 1.4 to 10.7 GHz, provided by the other authors [15-19]. Later it was reported [14] that the Hydra A flux density in 1990 had decreased, relative to the late 60s and early 70s, with frequency dependence from 0.4% at 1408 MHz to 4.7% at 10550 MHz. Therefore, with account of Hydra A flux density reduction at 1667 MHz, the annual decay rate for SNR1604, averaged over the period 1967.5 to 1987.5 should be taken as $(0.2 \pm 0.07)\%$. (Note that corrections at 5870 MHz are impossible, due to the complicated character of Hydra A's flux variations in the centimeter waveband and the absence of relevant observations).

3. *Results.* Energy parameters of SNR1572 and SNR1604 are given in Table 4.

Table 4

TYCHO AND KEPLER SNRs ENERGY PARAMETERS

Parameter	SN1572	SN1604
X-ray luminosity (0.15 to 4.5 MeV), erg s^{-1}	$7 \cdot 10^{35}$ [20]	10^{36} [21]
Mean electron density, cm^{-3}	5 [22]	7 [23]
Radio luminosity (15 to 10000 MHz) erg s^{-1}	$2.94 \cdot 10^{31}$	$2.12 \cdot 10^{31}$
Spectral index	0.625 ± 0.003	0.646 ± 0.01
Magnetic field strength, Gs	$4.3 \cdot 10^{-4}$ [24]	$7.4 \cdot 10^{-5}$ [22]
Magnetic field energy density U_m, erg cm^{-3}	$7.36 \cdot 10^{-9}$	$2.18 \cdot 10^{-10}$
Relativistic electrons energy density U_e, erg cm^{-3}	$1.1 \cdot 10^{-11}$	$4.4 \cdot 10^{-10}$
U_e/U_m	$1.5 \cdot 10^{-3}$	2
Relativistic electron energy ($\nu = 15$ MHz), eV	$8.7 \cdot 10^{7}$	$2 \cdot 10^{8}$
Mean decay rate, %	0.47 ± 0.05	0.2 ± 0.07
Mean expansion parameter	0.462 [4]	0.5 [5]

Note that these SNRs have practically equal luminosity values in the radio and X-ray parts of the spectrum, but are distinct in magnetic fields and relativistic electron energies, as well as the decay rates of their luminosities:

$$\left(\frac{U_e}{U_m}\right)_{SNR1604} \gg \left(\frac{U_e}{U_m}\right)_{SNR1572};$$

$$(U_e)_{SNR1604} \gg (U_e)_{SNR1572};$$
$$(U_m)_{SNR1604} \ll (U_m)_{SNR1572}; \qquad (1)$$
$$\left(\frac{1}{L_\nu}\frac{dL_\nu}{dt}\right)_{SNR1604} \approx 0.5\left(\frac{1}{L_\nu}\frac{dL_\nu}{dt}\right)_{SNR1572}$$

Assuming that relativistic electrons have inverse power law of energy distribution $N_e(E) = KE^{-\gamma}$, where E is energy and K is some constant, the synchrotron radiation luminosity may be expressed as follows:

$$L_\nu \approx 4\pi R^2 \Delta RKB^{(\gamma+1)/2} \nu^{-(\gamma-1)/2}, \qquad (2)$$

where ΔR is the radio shell thickness, $R \propto t^m$ and where t is the expansion time, B is the magnetic field strength. In the radio emission models, the annual rate of decay of luminosity L_ν has four versions of the power law [25]. For the SNR1572, the rate $(1/L_\nu)(dL_\nu/dt) \approx -0.5\%$, so that the best fit is the standard (version 1) model [26], where $K \propto t^{-2}$ and $B^2 \propto t^{-2}$. If the only losses are due to adiabatic expansion of the remnant, then $E \propto R^{-1}$, so that in our case $E \propto t^{-0.5}$.

The time dependence of the constant K is evaluated from the expression for energy density of relativistic electrons; $U_e = n\overline{E} \propto R^{-4} \propto t^{-2}$, where n is the electron density in cm^{-3} and $\overline{E}$ is their average energy. One also has the relation:

$$U_e = K\int_{E_*}^{\infty} E^{-(\gamma-1)}dE = \frac{1}{\gamma-2}KE_*^{2-\gamma} \propto t^{-2} \qquad (3)$$

In the case SNR1572, we obtain $K \propto t^{-1.9}$, hence the acceleration of relativistic electrons is absent in the modern epoch. In the case of SNR1604 $(1/L_\nu)(dL_\nu/dt) = -0.2\%$, so that no version of radio emission model corresponds to that value. The closest is version 3, with $K \propto R^{-2}$ and $B^2 \propto t^{-2}$, for which $(1/L_\nu)(dL_\nu/dt) = -0.3\%$. The observed value of the luminosity decline corresponds to a time dependence $K \propto t^{-0.63}$ and $B^2 \propto t^{-2}$, which indicates the existence of a strong acceleration process inside this remnant.

4. *Conclusions*. The character of the radio luminosity evolution and energy densities of the magnetic fields and the relativistic electrons are essentially different in SNR1572 and SNR1604. Therefore, these remnants should be considered as belonging to different type of supernovae. SN1604 is classified as type SNIb or SNII [7,27] and expects its progenitor to be a massive star having a lower limit of total mass $M > 10\,M_\odot$.

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ЭВОЛЮЦИЯ РАДИОСВЕТИМОСТЕЙ ОСТАТКОВ СВЕРХНОВЫХ ТИХО И КЕПЛЕРА

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Рассмотрены радиоизлучение исторических остатков сверхновых Тихо (ОСН1572) и Кеплера (ОСН1604), а также эволюция их яркостей. Данные о скорости векового уменьшения их яркостей, измеренные ранее авторами, сопоставлены с изменениями во времени плотностей потоков источников сравнения. В результате установлено, что яркость ОСН1604 на частоте 1667МГц ослабевает со средней годовой скоростью, равной $(0.2 \pm 0.07)\%$. Аналогичная скорость для ОСН1572 составляет $(0.47 \pm 0.05)\%$. Поскольку эволюция радиояркости, а также плотности энергии магнитного поля и релятивистских электронов внутри ОСН1604 и ОСН1572 существенно отличаются друг от друга, их следует рассматривать как сверхновые различных типов. Бандиера относит СН1604 к типу СНIв или СНII.

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