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RADIO EMISSION FROM VELA SUPERNOVA REMNANT

The radio emission from the Vela Supernova remnant (SNR) was simulated in the framework of our new model [3], which explains peculiarities of the X-ray emission of the Vela SNR by the essential influence on the dynamics of the remnant of the evaporation of clouds, which give the dominant input into the interstellar medium (ISM). The obtained volume integrated flux density and morphology of the Vela SNR are in a good agreement with observations, what confirms the new model of the Vela SNR.

Розглянуто радіо-випромінювання від залишку Наднової (ЗН) Вітрила в рамках нашої нової моделі [3], що пояснює особливості рентгенівського випромінювання ЗН суттєвим впливом на динаміку залишку випаровування хмар, які вносять домінуючий вклад в середню густину міжзоряного середовища (МЗС) навколо залишку. Отримані інтегральна густина радіо-потоку і морфологія залишку добре узгоджуються зі спостережними даними, що є незалежним підтвердженням нової моделі ЗН Вітрила.

1. Introduction. Vela Supernova remnant (SNR) is one of the most studied and closest to the Earth SNRs. The age and the distance to the Vela SNR are well determined what makes it a perfect object for the investigation of the physical processes. It is also accompanied by Vela pulsar and its pulsar wind nebula (PWN) Vela X what makes it even more interesting. The age of the Vela SNR is determined as the age of the pulsar and is about 1.1×10^4 years [1]. The distance to the remnant is determined from the VLBI parallax measurements of the Vela pulsar and is around 287 pc [2].

Vela SNR is one of the brightest sources on the sky in radio and X-ray bands. The X-ray emission appears to be dimmer but more extended in the south west (SW) part in comparison to the north east (NE) part. This is explained within the assumption that Vela SNR progenitor supernova exploded on the border of the stellar wind bubble of the nearby Wolf-Rayet (WR) star in the binary system γ^2Velorum [3]. According to this model Vela SNR is expanding into media of different densities.

The X-ray emission from the Vela SNR is distributed all over the SNR without any evidence of the main shock. This peculiarity is naturally explained by the expansion in a very inhomogeneous cloudy interstellar medium (ISM) [3]. In this case the emission comes mainly from the heated and evaporated matter of clouds. The explosion energy of the supernova within this model is $E = 1.4\cdot10^{50}$ ergs.

In this paper the synchrotron radio emission from the Vela SNR is simulated in the framework of the same model which assumes the supernova explosion on the border of the stellar wind bubble and the cloudy ISM.

2. Radio emission from the spherical SNR in the cloudy ISM. Synchrotron radio emission from the remnant expanding in the cloudy ISM is different from the one in the homogeneous ISM. The interaction of the main shock with clouds causes formation of secondary shocks on which the sufficient electron acceleration takes place. This leads to the close to uniform distribution of relativistic electrons inside the SNR. Thus, the luminosity of the SNR will grow towards the center where more electrons are situated on the line of sight. It differs from usual shell-type SNRs where relativistic electrons are concentrated in the shell of the remnant.

In the first approximation relativistic electrons are uniformly distributed within the remnant. The energy spectrum of electrons $N_e(\gamma)$ is assumed to follow the power-law:

$$\frac{dN_e}{d\gamma} = K_e \gamma^{-p},$$

where γ is the electron Lorentz factor, K_e is a constant and p is an electron spectral index.

Then the overall (volume integrated) synchrotron luminosity density at frequency from the spherical SNR can be calculated as [4]:

$$S_\nu = \left(\frac{4}{3}\pi R^3\right) K_e \frac{\sqrt{3} q^3 B \sin\alpha}{mc^2(p+1)} \Gamma\left(\frac{p}{4}+\frac{19}{12}\right) \Gamma\left(\frac{p}{4}-\frac{1}{12}\right) \left(\frac{2\pi mc}{3qB\sin\theta}\nu\right)^{-\frac{(p-1)}{2}},$$

and integrated flux density is $F\nu = S\nu / 4\pi D2$, where B is the magnetic field, R is the radius of the SNR, q is the electron-charge, m is the electron mass, c is the speed of light, D is the distance to the SNR, and θ is the angle between the magnetic field and electron velocity. It is assumed that electron velocities are isotropically distributed and a spherically averaged value $\sin\theta = \sqrt{2/3}$ can be used.

The luminosity density depends on three parameters, namely radius of the SNR R, magnetic field inside the SNR B and constant K_e, which is related to the density of relativistic electrons. The radius of the remnant can be calculated straightforward from the value of the distance to the remnant and its angular size. For the estimation of the magnetic field one can use the equilibrium condition of the magnetic pressure and the thermal pressure of particles. Then, if the number density and the temperature are known the value of the magnetic field can be calculated (see [5,6] for details). And finally to calculate one should know a total energy in relativistic electrons and a size the remnant [5,6]. Therefore and can be estimated as following: $B = \sqrt{8\pi n k_B T}$ ' and

$$K_e = \frac{E_e}{\frac{4}{3}\pi R^3 mc^2 \int_{\gamma_{\min}}^{\infty} \gamma^{-p+1} d\gamma}$$

where n is a number density of particles, k_B is a Boltzmann constant, T is an average temperature of plasma inside the SNR, E_e is a total energy in relativistic electrons which can be assumed as 10^{-3} of the whole explosion energy E_{SN} and $mc^2\gamma_{\min}$ is assumed to be 1 GeV.

3. Radio Emission from Vela SNR. The observed X-ray morphology of the Vela SNR can be described as the combination of two hemispheres with different radii [3]. According to the assumption that the progenitor supernova was exploded on the border of the stellar wind bubble [3] SW and NE parts of the remnant are expanding into different media with different densities causing the asymmetry. For the modeling of the synchrotron emission we use a model described in [3] which states that Vela SNR consists of two hemispheres with radii pc and pc of NE and SW parts, correspondingly.

We assume that the explosion of the supernova was spherically symmetrical. This means that the total energy in relativistic electrons in SW and NE parts of the remnant are the same and equal. This causes that densities of relativistic electrons are different in SW and NE parts. From the equations presented in the previous section one can calculate magnetic fields (using values of particle number densities and temperatures obtained in [3]), and electron densities in SW and NE parts of the remnant. These values are gathered in the Table 1.

Table 1

Physical parameters in SW and NE parts of the Vela SNR calculated in this paper

SNR part	B, μG	n_e, $\times 10^{-6}$ cm^{-3}	K_e, $\times 10^{-6}$ cm^{-3}
SW	23	0.7	1.0
NE	35	1.5	2.1

Using obtained values for magnetic fields and electron densities in SW and NE parts of the remnant and assuming the electron spectral index , which is consisting with a radio spectral index presented in [7] (the relation between the electron spectral index and radio spectral index is), one can calculate the volume integrated flux density from the whole SNR F_V at different frequencies. On the Fig.1 we show the simulated flux density (solid line) together with the observational results obtained in [7] (black circles). As it is seen from the plot the obtained flux density is in a good agreement with observations. Note, that in [7] the observation of the whole region is presented including PWN Vela X while in this paper only flux from the Vela SNR is modeled. It means that comparing with observation data one should not take into account the observed flux from Vela X.

The asymmetry is also revealed in the radio morphology of the Vela SNR. According to [7] apart of the Vela X peak four other local peaks of the radio emission are distinguished, namely, peaks of Vela Y, Vela Z and two peaks of Vela W. These peaks can be well explained in the framework of the model of asymmetrical Vela SNR shape. On Fig. 2 we show the simulated brightness temperature map of the Vela SNR at 408 MHz. The emission is modeled in 3D where every volume unit is taken as a separate emitter and then it is projected on the observation plane, i. e. how it is seen in equatorial (RADec) coordinates. The position of the remnant in the space matches the geometry described in [3]. In this simulated brightness temperature map two local maximums can be easily allocated. The one in NE part, the hottest one, matches locations of the Vela Y and Vela Z peaks and the one in SW part matches the locations of two Vela W peaks. The value of the brightness temperature is also in a good agreement with observation data presented in [7].

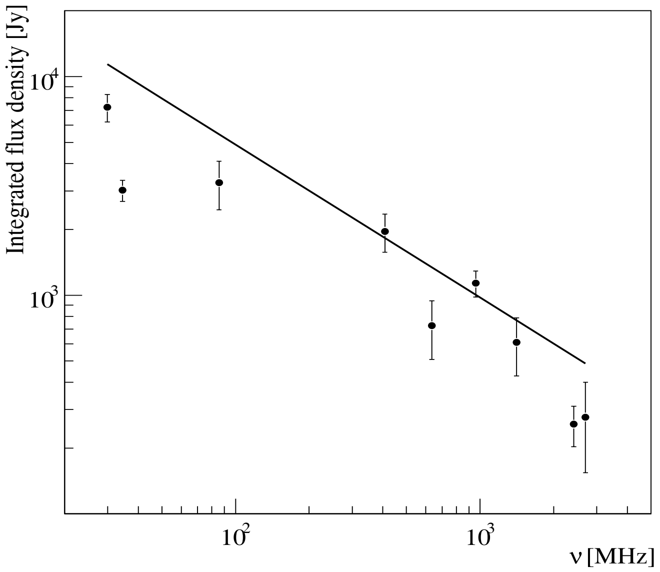

Fig. 1. Integrated flux density spectrum.
The straight line represents simulations presented in this paper. Points represent observational data [7]

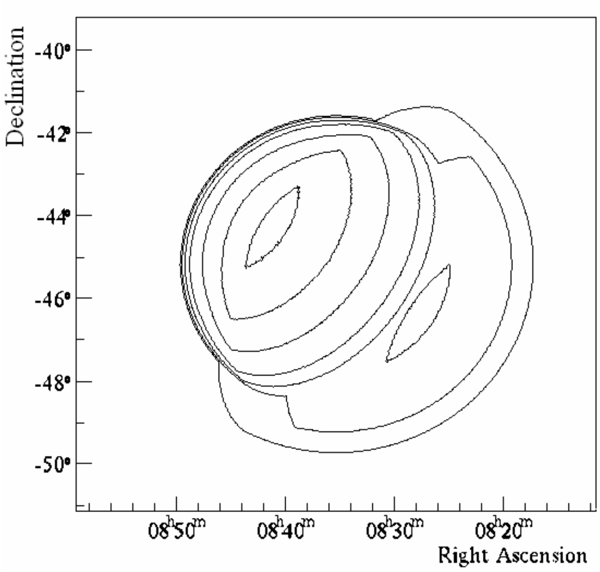

Fig. 2. Simulated brightness temperature map of the Vela SNR at 408 MHz.
The contours are labeled in K and contour values are: 2, 8, 14, 20, 30, 40 and 50 K

5. Conclusions. The radio emission from the Vela SNR was simulated within the hydrodynamical model presented in [3]. Both the flux values and the morphology are in a good agreement with the experimental data giving additional observational support for proposed in [3] new model of Vela SNR.

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