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A new model for Vela Jr. Supernova Remnant

I. Telezhinsky *

Astronomical Observatory of Kiev University, Observatorna 3, Kiev 03053, Ukraine

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ABSTRACT

We consider Vela Jr. as being the old Supernova Remnant (SNR) at the beginning of the transition from adiabatic to radiative stage of evolution. According to our model, Vela Jr. is situated outside Vela SNR at the distance of $\sim$600 pc and its age is 17500 yr. We model the high energy fluxes from Vela Jr. and its broadband spectrum. We find our results compatible with experimental data in radio waves, X- and γ-rays. Our hydrodynamical model of Vela Jr. explains the observed TeV γ-ray flux by hadronic mechanism. The proposed model does not contradict to the low density environment of the SNR and does not need extreme fraction of the explosion energy to be transferred to Cosmic Rays.

1. Introduction

It is widely discussed that Supernova Remnants (SNRs) are among the most promising galactic candidates for the Cosmic Rays (CRs) accelerators up to the energy of 10^{14}–10^{15} eV (see [1,2] and references therein). The direct evidence for the acceleration of leptonic component of CRs in SNRs is synchrotron emission in a broad domain of the electromagnetic spectrum ranging from radio to X-rays. In the same time we are missing the direct evidence for the hadronic acceleration in SNRs. This is important point because the composition of CRs is mainly hadronic according to the observed CR flux and predictions of acceleration theories. The very promising mechanism for the proof of the hadronic acceleration in SNRs would be the decay of neutral pions originated in the collisions of relativistic protons with protons at rest. The π^0-decay would result in γ-ray flux from the remnant or an SNR-molecular cloud system [3–5].

Therefore, after the detection of γ-rays from SNRs (with available instruments) it is crucial to know the nature (leptonic or hadronic) of the mechanism responsible for the production of the high energy flux. Both mechanisms inverse Compton (IC) and π^0-decay can contribute to the spectrum domain that modern instruments operate. The lack of a viable model that self-consistently explains physical conditions in the SNRs and lets unambiguously determine the production mechanism is important problem of the modern astrophysics and CR science. Even in well known detected by the H.E.S.S. collaboration γ-ray SNRs (RX J1713.7-3946 [6–8] and RX J0852.0-4622 [9,10]) the mechanism of the origin of γ-rays is still questionable. A broad MeV to multi TeV study of the objects is required to favour or reject the hadronic γ-ray production mechanism [11].

In our previous works [12,13] we showed that it is possible to expect the high energy γ-ray flux from the old SNRs at the transition from adiabatic to radiative stage of evolution. The high γ-ray flux from the SNRs evolving in either uniform or non-uniform ISM appears when the dense shell forms during the transition stage. The dense shell plays the role of the target material for the high energy CRs. We also showed that during the dense shell formation the thermal X-ray flux decreases because the significant amount of the SNR gas cools down. The low thermal X-ray and high γ-ray fluxes predicted by our model to exist in the same one SNR are the cases of the recently detected γ-ray SNRs (RX J1713.7-3946, RX J0852.0-4622). This gave us a hint to apply our model for the explanation of their nature.

In the current work we apply our hydrodynamical model [14,15,12,13] of the transition stage of SNR evolution to explain the observed broadband spectrum (radio, X- and γ-ray) of Vela Jr. Supernova Remnant. The transition stage itself was first studied numerically in [16] and the estimates of the different reference times connected with the transition stage were reviewed in [17].

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* Tel.: +380 979202336.
E-mail addresses: igor_space@ukr.net, igor_t@online.ua

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Originally, Vela Jr. (or RX J0852.0-4622) was discovered by Aschenbach in 1998 [18] from the ROSAT All-Sky Survey data. It is located in the south-eastern corner of Vela SNR, so in soft X-rays it is masked by the emission from Vela SNR and is visible only above ~1 keV. The emission from Vela Jr. is dominated by non-thermal component with photon index $\Gamma \sim 2.6$ [19]. The remnant is visible in radio band [20]. The radio flux is weak ($S_\nu = 30$–50 Jy at 1 GHz) with faint, limb-brightened emission similar to the X-ray morphology [21]. The study of Vela Jr. is complicated due to the high background created by Vela SNR. The distance and the age of the remnant are still unknown. The recent detection by Cherenkov telescopes [22,9] of the TeV γ-ray emission from Vela Jr. and the fact that it is one of the few SNRs with non-thermal dominated emission made it an object of intensive studies [23,19,24,10].

In what follows we briefly describe the hydrodynamics of the transition stage (Section 2). Then we apply our hydrodynamical model to Vela Jr. (Section 3) and derive the hydrodynamical and CRs parameters for the spectrum modelling (Section 4). The broadband spectral model and γ-ray surface brightness map of Vela Jr. are presented in Section 5. We make a short discussion of the obtained results in Section 6 and conclude in Section 7.

2. Transition stage model

2.1. Origin and dynamics of the thin shell

The full description of the transition stage model is given in [14,15]. Here we outline the most important features.

Numerical simulations [16,25] show that radiative losses become important at the time:

$$t_{tr} = 2.9 \times 10^4 E_{51}^{4/17} n_{\rm ISM}^{-9/17}\ {\rm yr}, \tag{1}$$

where E_{51} is the explosion energy in 10^{51} ergs, $n_{\rm ISM}$ is the ISM number density in cm^{-3}.

Radiative losses lead to rapid formation of the cold dense shell near the front. When the hot SNR gas joins the inner boundary of the shell it cools down leading to the growth of the shell. The shell grows as well because it sweeps up the ISM. The transition phase ends when the hot gas stops cooling effectively and no more replenishes the shell. We use the numerical results [16] saying that cooling is important for the hot plasma within the outer 5% ($\alpha = 0.05$) of the SNR radius at the beginning of the transition phase: $\Delta r = \alpha R_{tr}$. Parameter α is the only free parameter of our model of the transition stage of SNR evolution.

For the beginning of the transition stage we take the time t_{tr}. It is the time when the first cold gas element of the shell appears at the shock front. The element has temperature T_{sh}, pressure P_{sh}, density ρ_{sh} and velocity V_{sh}. From the balance of external and internal pressure on the shell $\rho_{\rm ISM} V_{sh}^2 = \rho_{tr}(v_{tr} - V_{sh})^2$, we derive the velocity of the shell for the adiabatic index $\gamma = 5/3$:

$$V_{sh} = \frac{1}{2} D_{tr} = const \tag{2}$$

where $\rho_{\rm ISM}$ is the ISM density, ρ_{tr} and D_{tr} are the shock front plasma density and velocity for the time t_{tr}, $v_{tr} = 0.75\, D_{tr}$ is the plasma velocity just behind the shock front. We assume that during the transition stage a small pressure gradient inside the SNR results in conservation of the velocity of each plasma element unless and until it joints the shell:

$$v(a,t) = \begin{cases} v(a,t_{tr}) & \text{if } 0 < a < a_c(t) \\ V_{sh} & \text{if } a_c(t) < a < R_{tr} \end{cases} \tag{3}$$

where $a_c(t)$ is the Lagrangian coordinate of the gas element that cools at the time t. For the end of the transition phase $a_c(t_{sf}) \simeq 0.78$. The duration of transition phase in our model is:

$$\Delta t = t_{sf} - t_{tr} = \frac{\alpha R_{tr}}{v(0.78, t_{tr}) - V_{sh}} \tag{4}$$

2.2. Hot gas parameters inside the shell

For the time $t_{tr} < t < t_{sf}$ the velocity of the gas element with the Lagrangian coordinate $0 < a < a_c(t)$ is given by Eq. (3), so for the Euler coordinate $r(a,t)$ we have:

$$r(a,t) = \begin{cases} r(a,t_{tr}) + v(a,t_{tr})(t - t_{tr}) & \text{if } 0 < a < a_c(t) \\ R_{sh} & \text{if } a_c(t) < a < R_{tr} \end{cases} \tag{5}$$

The density distribution $\rho(a,t)$ we find from the continuity condition:

$$\rho(a,t) = \rho(a,t_{tr}) \left(\frac{r(a,t_{tr})}{r(a,t)} \right)^2 \frac{dr(a,t_{tr})}{dr(a,t)} \tag{6}$$

the hot gas pressure is:

$$P(a,t) = P(a,t_{tr}) \left(\frac{\rho(a,t)}{\rho(a,t_{tr})} \right)^\gamma \tag{7}$$

and the temperature:

$$T(a,t) = \frac{\mu P(a,t)}{R_g \rho(a,t)} \tag{8}$$

where R_g is the absolute gas constant, μ is the molar mass. Thus we give the full description of the hot gas inside the SNR. This gives us a possibility to model thermal X-ray emission of the remnant.

2.3. Cold shell gas parameters

Starting from the time t_{tr} the mass of the shell increases because the interior hot gas cools and joins the shell and the shell sweeps up the ISM. The temperature of the shell equals the ISM temperature: $T_{sh} = T_{\rm ISM} = 10^4$ K and its pressure P_{sh} equals the dynamical pressure on the shell. See Section 4 for detailed discussion of the shell parameters.

3. The hydrodynamical model of Vela Jr.

In the current section we apply our model of the transition stage to Vela Jr. The high energy flux from Vela Jr. is difficult to explain by π^0-decay mechanism because in order to obtain the sufficient amount of p–p collisions the number density of the ISM in the vicinity of Vela Jr. should be high. The high density of ISM contradicts to very weak thermal component of the observed X-ray flux. The weak thermal X-ray emission puts an upper limit on the ISM density. The other possibility to explain the observed γ-rays by π^0-decays is to have a higher fraction of the explosion energy transferred to CRs during the acceleration history. However, in this case we need almost all the explosion energy to be transferred to CRs (see Table 1 in [10]), which is not a plausible solution of the problem.

As was shown above (Section 2), the advantage of our hydrodynamical model is that the high density cold shell forms at the front region of the remnant during the transition stage. The CRs contained in the cooled volume of the SNR start interacting with the dense target material of the shell, thus providing an increased π^0-decay γ-ray flux. We use this advantage to build the model of Vela Jr.

We assume that Vela Jr. is rather old SNR that has gone through the adiabatic stage of evolution and is at the transition stage. We assume it is at moderate distance and do not consider a close-by scenario for several reasons. Firstly, because the observed absorption is rather high ($N_H \sim 6.2 \times 10^{21}$ [10]). Secondly, in our model it is old SNR and unless the density of ISM is high (but this contradicts the observations) the radius should be quite large. Finally,