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Consequences of Cosmic Ray Acceleration in Supernova Remnants on their Evolution – the Case of RX J0852.0-4622 (Vela Jr)

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Galactic cosmic rays are generally assumed to be accelerated in supernovae and their remnants. The acceleration of the particles is attributed to their repeatedly interaction with the supernova remnant shock front. Model calculations have shown that a significant fraction of the supernova explosion energy can be converted to energy of cosmic rays. The feedback of this large energy transfer on the dynamical evolution and its impact on the age estimates of supernova remnants is addressed. True ages might be significantly lower than the standard Sedov ages. The impact is described by a quantitative model, which is tested on RX J0852.0-4622 (Vela Jr). Independent of this test conclusions are drawn about the evolution and lifetime of shell-type X-ray synchrotron sources and TeV gamma-ray sources associated with supernova remnants.

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1. Introduction

Galactic cosmic rays have been suggested to be generated in supernova remnant shock fronts. The energies should reach up to 100 TeV for electrons and up to 10^{15} eV for protons. The observation channels to pin-point an individual source are the observation of hard X-ray synchrotron radiation, i.e., >1 – 2 keV, and/or of TeV gamma-rays produced by either the inverse Compton effect of high energy electrons with background photon radiation, and/or the high energy protons accelerated via their SNR shock interaction producing TeV gamma-rays by nuclear collisions with ambient nuclei, predominantly protons.

There are about 294 catalogued galactic SNRs identified as such by their radio emission, about half of them have been detected in X-rays, much less in the optical band. But so far only three SNRs have been found to radiate synchroton X-rays and TeV gamma-rays from regions confined to their shock fronts. There are other sources with TeV gamma-ray emission and synchrotron X-rays, like the Crab Nebula, but the emission is from all across the source extent and not confined to the shock front. Therefore these sources are not considered in this study. Three questions arise:

1. why are there so very few objects, if cosmic ray acceleration in SNR shock fronts would be the main source of galactic cosmic rays;
2. is a special type of SN required for shock acceleration;
3. is the environment around the explosion cloud of importance.

The three SNRs which show X-ray synchrotron emission and TeV gamma-rays are SN1006 with both thermal and synchrotron X-ray emission and possibly TeV gamma-rays, RX 1713.7-3946 with synchrotron X-rays, lacking thermal X-rays from the outer shock front completely, and TeV gamma-rays, and RX 0852.0-4622, again without any sign of thermal X-rays but synchrotron X-rays and TeV gamma-rays. What is special about these three SNRs concerning cosmic ray acceleration in shock fronts?

2. Creation of cosmic rays by SNR shock acceleration

The generation of cosmic rays in shocks is treated using the ´theory of non-linear diffusion-like acceleration of particles by their interaction with shock waves´, for instance, at the front of shell-type SNRs. Among the results of the application of this theory with respect to SN1006 (Ksenofontov et al., 2005) are firstly, that the energy in cosmic rays can reach 55% of the total SN explosion energy, secondly, the acceleration time scale can range between just 300 and 700 years, depending weakly on the ambient matter density, and, thirdly the energy increase in cosmic rays saturates after 2000 – 3000 years, and the energy is not replenished. In particular, I think, which has not been considered so far, is that the fairly large transfer of energy to cosmic rays should have an effect on the dynamical evolution of the SNR.

As far as I know there is no analytic expression available to describe the time dependence of cosmic ray shock acceleration. Nevertheless, there may be a reliable approximation which is derived using the following seven relations.

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$$\Delta v_{cr} \sim v_s \quad (1)$$

$$\Delta v_{cr,g} \sim v_s \Delta(t^{1/2}) \quad (2)$$

$$dE_{cr} \sim v_s^2 \, dt \quad (3)$$

$$E_{SN} = E_s + E_{th} + E_{kin} + E_{cr} \quad (4)$$

$$E_{th} + E_{kin} \sim v_s^2 \sim E_{SN} - E_{cr} \quad (5)$$

$$dE_{cr} \sim -(E_{cr} - E_{SN}) \, dt \quad (6)$$

$$E_{cr}/E_{SN} \sim [1 - \exp(-t/t_{cr})] \quad (7)$$

The shock velocity is v_s . Δv_{cr} is the increase of the velocity of an ambient proton by crossing the shock which eventually becomes a cosmic ray particle, t is the time, E_s is the energy reservoir of the shock, E_{th} is the thermal energy and E_{kin} is the kinetic energy, respectively, transferred to the ambient matter that passed the shock. Equation 1 illustrates the fundamental process of accelerating ambient particles extracting velocity and energy from the shock and the associated magnetic field for a single crossing, though. Equation 2 is an attempt to describe the process progression, i.e., how the velocity of the suspected cosmic ray particle grows with time, $\Delta v_{cr,g}$. Subsequent crossings of the particle can increase its velocity, but of varying amount, even slowing down its velocity, occasionally. This is why the process is non-linear in time. In fact, it is a diffusion-like process in velocity space. Diffusion-like processes vary with $t^{1/2}$. On incremental scale, the result is Eq 2. Eq. 3 is obtained by changing from velocity space to energy space, by squaring $v_{cr,g}$,v_s, $t^{1/2}$. Equation 7 shows the resulting relation between total cosmic ray energy and SN explosion E_{SN}. It is an exponential with some e-fold time t_{cr} which depends on the up-stream magnetic field, its magnitude and morphology, the up-stream matter density, the injection rate of suprathermal particles and their velocity distribution. Comparison with the results of the non-linear theory done for SN1006 by Ksenofontonov et al. (2005) shows that an exponential growth of cosmic ray energy content is not too bad an approximation.

3. Modification of the Sedov relation

The general view of the dynamical evolution of SNRs is that the expansion of the explosion of a SN propagating into the ambient environment starts with a phase of free expansion, which at some time, depending on the ambient matter density n, changes to the so-called Sedov-phase, which is energy conservation dominated and during which the expansion velocity of the explosion cloud, i.e., the shock front, slows down with time t, indicated by the shock radius r increasing less than proportional to t.

$$r = \mathrm{const}\,(E_{SN}/n)^{1/5}\, t^{2/5} \quad (8)$$

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Measuring the shock velocity and the shock radius the age of the SNR is estimated by t_{Sedov} = 2/5 r/v_s .This relationship takes care of the energy transfer to kinetic and thermal energy from the shock, which causes the slow-down, but not of the energy losses pumped in cosmic rays. As a working hypothesis I suggest that the original Sedov relation should be modified to take care of the cosmic ray energy consumption. I will use the following relation

$$E_{cr}(t)/E_{SN} = A\,[1 - \exp(-t/t_{cr})] \tag{9}$$

such that the original Sedov relation is modified to the following equation 10.

$$r = \text{const}\,(E_{SN}/n)^{1/5}\, t^{2/5}\,(1\text{-}A\,[1 - \exp(-t/t_{cr})])^{1/5} \tag{10}$$

The immediate effect is that the age of the SNR derived from r and v_s changes compared to t_{Sedov}. The ratio of r/v_s using equation 10 with v_s the time derivative of r shows a single maximum for the parameter $2r/(5v_s t) = t_{Sedov}/t = k$ for each value of A. This means that the age of the SNR could be lower than the Sedov age by this factor k. For low values of A the reduction in age is negligible, but for higher values of A the age reduction is significant. For example, A = 0.5, k=1.16; A=0.7, k=1.35; A=0.90, k=2.22; A=0.95, k=4.2. The use of the Sedov age as an age estimate becomes fairly unreliable, if A is approaching values of 0.7 and more. Assuming that this is physically possible, a test object would be, as mentioned in the introduction, RX 0852.0-3946 (Vela Jr) .

4. A test object

RX 0852.0-3946 (Vela Jr) was discovered during the ROSAT All-Sky-Survey in X-rays (Aschenbach, 1998). A gamma-ray line excess above the background signal due to radioactive ^{44}Ti was found (Iyudin et al., 1998), which, because of its short life-time of 90 years led to the conjecture that this SNR would be young, about 700 years, and because of its X-ray extent should be close-by, maybe as close as 200 pc (Aschenbach et al., 1999). The result of Iyudin et al. concerning the ^{44}Ti signal has not been confirmed by later measurements, the analyses of which, however, are restricted to a point-like source.

Several findings indicate that very unusual celestial events had happened in the 13th century, which might be attributed to a nearby SN. These are, among others, nitrate precipitation markers in Arctic drilled ice cores (Burgess & Zuber, 2000); sudden increase in atmospheric radiocarbon; the bright star, the Zimbabwe star, probably observed from the Great Zimbabwe monument (Wade, 2015). From Japan, there is a report that on September 12, 1271 an object as bright as the full moon suddenly appeared on the sky about 10 degrees above the horizon, which marks the beginning of the rise of Nichiren Buddhism. All these findings are consistent with the occurrence of a SN in 1271.

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The measured properties of Vela Jr are r = 1°; v_s = 0.84 arcsec/yr (Katsuda et al., 2008); n<0.029 $d_1^{-1/2}$ (Slane et al., 2001); E_{cr} = $2.5{\cdot}10^{50}$ erg · d_1^{2}/n (Aharonian et al. 2007), if the TeV gamma-ray emission is exclusively attributed to π^0 decay emission. d_1 is the distance measured in units of 1 kpc and n is the particle density in cm^{-3}.

The Sedov age determined from the X-ray observation is 1714 years. If the true age would be 730 years (SN in 1271) a minimum value of A=0.9075 is required. For t measured in units of 10000 years, n in cm^{-3} and E_{SN} in 10^{51} ergs, the const in equation 10 is 14 pc. Applying the modified Sedov relation (Eq. 10) it turns out that for a canonical value of $E_{SN}=10^{51}$ erg, n=0.041 cm^{-3} and the distance to the SNR is d=386 pc. The cosmic ray e-fold growth time t_{cr}=338 years. The values of n and d are fairly insensitive to $t_{cr,}$ which could be up to 700 to 800 years for larger values of A without changing the results of n and d significantly. Reconstructing the velocity time profile shows that the early velocity of the SNR must have been fairly high, i.e. 40000 km/s at t=20yrs and 20000 km/s at t=40 yrs. The current, today´s, velocity would be v_s=1536 km/s .
Equation 10 implies that t becomes fairly insensitive to the ratio of r/v_s for values of A >0.9. Allen et al. (2015) have measured the shock velocity and radius at a different rim position of the SNR obtaining an estimated Sedov age 1.7 times larger than the result of the measurements of Katsuda et al. (2008) indicate. Raising the value of A to A=0.946 the age of the remnant could be still 730 years. The distance would be d=368 pc, the density n=0.036 cm^{-3} and t_{cr}=300 years. In this case the current, today´s, velocity would be v_s=732 km/s .

5. Conclusions

The three SNRs mentioned, i.e., RX 0852.0-4622, RX 1713.7-3946 and SN1006, appear to have in common a very low ambient density of something <0.05 cm^{-3}. This suggests that the progenitor star was not likely to be a red supergiant because of the much higher density of the wind embedding such a star at the time of its explosion. This leaves blue supergiants as a possible source or SN type Ia events. This argument is strengthened by the early very high expansion speed, exceeding the generally accepted values of 10000-20000 km/s. SN1987A showed a mean expansion velocity of 40000 km/s averaged over the first six years. It appears, that a low ambient matter density and a high explosion velocity, rather than high explosion energy, favor the efficient shock acceleration of particles. That the initial explosion velocity is important is evident from equation 1. The relevance of ambient density n, is obvious from comparing the loss of shock energy to kinetic and thermal energy of the shocked plasma, which increases with n, whereas the cosmic ray energy production increases with $n^{3/16}$ (Ksenofontov et al., 2005). For a value, for instance, of n=0.06 cm^{-3} the particle/cosmic ray acceleration efficiency would be 10 times higher in energy transfer than plasma heating.

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Given the values of t_{cr} suggested by the non-linear theory of shock acceleration, and independently in this study, the cosmic ray acceleration starts to saturate after 2000 - 3000 years without any further energy supplied because the shock velocity has become too low (c.f. Eq.1). With no further energy supply and no re-acceleration the cosmic ray particles are subject to radiation losses with the time-scale for electrons being fairly short. If they radiate their energy in an up-stream magnetic field of 5 μG the lifetime of the electrons producing 1 keV X-rays is 5800 years, and for those producing 10 keV X-rays the lifetime is 1800 years. If the ambient up-stream magnetic field is significantly higher than the typical galactic 5 μG, the lifetime is shorter, for instance, by a factor of about fifteen for a field strength of 30 μG. After a couple of a few hundred years the high energy electrons energy are gone and with them the high energy X-ray synchrotron radiation and the TeV gamma-rays if associated with the inverse Compton effect. What is left after at most a couple of a few thousand years is a fairly low surface brightness radio supernova remnant, and possibly a lot of cosmic ray protons, and who knows, isolated pulsars apparently unaccompanied by a supernova remnant.

The combination of low ambient density, high birth shock-velocity and short lifetime of SNR connected cosmic ray electrons might explain the rareness of this special type of SNRs among the SNR population.

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