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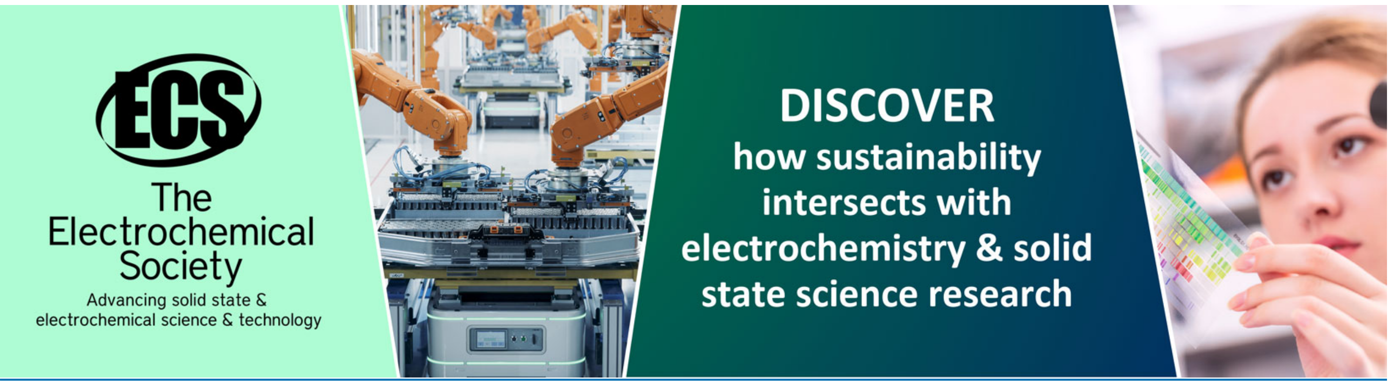

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2D axisymmetric model of particle acceleration in colliding shock flows system

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Abstract. We present the 2D axisymmetric model of particle acceleration at colliding shocks from supernova remnant and stellar wind from the nearby star. The model is the expansion of the previously developed plane-parallel model and takes into account three three-dimensional structure of the stellar wind and the supernova remnant shock. Numerical and analytical calculations provides the energetic and spatial distributions of the particles accelerated by colliding shock flows system. The presented model can be used in calculations of the emission spectra of different stellar associations and star clusters with colliding shock flows.

1. Introduction

The interaction of the supernova remnant (SNR) with the wind of a nearby massive star or the star cluster is the short-lived phenomenon. It should occur in young massive star clusters and OB-associations. This interaction leads to localized sources of X-ray and γ-ray emission embedded in the diffuse emission of the SNR. In the paper [1] there was noted that the emission arising in the SNR/stellar wind interaction is a substantial fraction of the total X-ray luminosity several thousand years after the SNR-stellar wind interaction. The simulations developed in [1] predict the presence of X-ray bright rings in that kind of sources. In the present paper we investigate the properties of these systems as the particle accelerator and the source of X-ray and γ-ray emission but a few hundreds years before the beginning of the shocks interaction.

We model a class of particle accelerators associated with the close approaching of a young SNR shock and a fast shocked stellar wind. Some basic features of such systems were noticed in our previous papers [2, 3]. In figure 1 there is presented the schematic view of the system. The modeled stage starts a few hundred years before the SNR shock collides with the wind termination shock when the distance between the shocks D_0 becomes less than 1 pc. At this stage the maximal energy particles accelerated via diffusive shock acceleration (DSA) mechanism at the SNR shock reach the fast wind termination shock and begin to scatter back by magnetic fluctuations carried by the fast stellar wind. Thus, the high energy particles that have mean free path $\Lambda(p)$ larger than D_0 start to be accelerated by converging fast flows. This is the most favorable circumstance for the efficient Fermi acceleration.

Numerical calculations based on the non-linear time-dependent model of particle acceleration in Colliding Shock Flows (CSF) system [2, 3] showed that these systems have a set of important properties. Maximal energies of the particles accelerated in these systems can be by the order of magnitude higher than in the case of an isolated SNR shock [4]. These sources can make a

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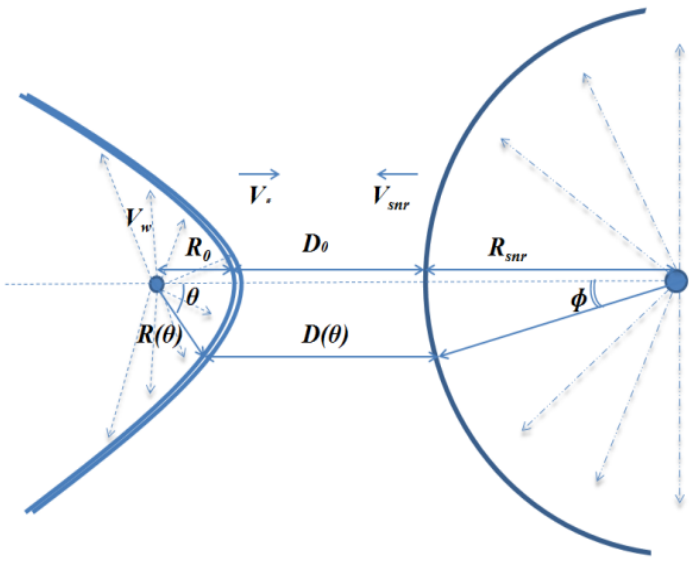

Figure 1. The schematic view of the modeled system. SNR shock approaches the bowshock of the nearby star.

significant contribution to the total flux of galactic cosmic rays (CR) in the high energy range at $10^{14} - 10^{17}$ eV [3]. The specific property of CSF system is that due to high efficiency of acceleration the particles have very hard spectral energy distribution (SED) with the spectral index $\gamma = 1$ during the time of efficient acceleration ($\tau_a \geq 300$ yr). The existing numerical codes provided the model spectra of X-ray and γ-ray emission from these sources [3, 5], that have a set of properties of a "dark accelerators" - non-identified sources of gamma-emission.

The non-linear plane-parallel model of particle acceleration at colliding shock flows did not account for the three-dimensional geometry of the flows. The main goal of this paper is to generalize the model for an arbitrary choice of flow velocities and imply the 3D model expansion with taking into account the shapes of the stellar wind bowshock and the SNR's shell. According to this new model we have calculated new SED of the particles accelerated in the source.

2. The geometry of the model

The shape of the stellar wind bowshock in the thin shell limit can be described as follows [6]:

$$R(\theta) = \sqrt{\frac{\dot{m}V_w}{4\pi\rho_a V_*^2}} \cdot \frac{\sqrt{3(1-\theta ctg\theta)}}{sin\theta} \tag{1}$$

where θ - is the angle between the symmetric axis and selected direction at the bowshock, $\dot{m}$ - is the mass loss rate of the star, V_w - the velocity of the stellar wind, ρ_a- is the density of the ambient medium, V_* - is the star velocity. The star is assumed to be situated in the origin ($R = 0$).

Assuming that the shape of the SNR shock is the sphere with the radius R_{snr} the distance between the bowshock and the SNR shock at arbitrary time moment t can be expressed as follows (see figure 1 for the illustration):

$$D(\theta) = D_0 + R_{snr}(1 - cos\phi) + \\ +R_0\left(1 - \frac{R(\theta)cos\theta}{R_0}\right) - (V_* + V_{snr}cos\phi)(t - t_0) \tag{2}$$

where D_0 - is the distance between the shocks at $t = t_0$ and $\theta = 0$, R_{snr} - is the radius of the SNR, $R_0 = R(\theta = 0) = \sqrt{\frac{\dot{m}V_w}{4\pi\rho_a V_*^2}}$ - is the radius of the stop point of the stellar wind, V_{snr} - is the velocity of the SNR shock, $\phi = \arctan\left(\frac{R(\theta)\sin\theta}{R_{snr}}\right)$. We have assumed above that the star moves parallel to the axis but in general case V_* should be replaced by $V_* * cos\psi$, where ψ - is the angle between the axis and the direction of star motion.

Equation (2) allows to calculate the distance between colliding shocks for any distance from the axis (different θ's).

3. Non-symmetric non-linear model of particle acceleration at CSF systems

Recently we have developed the semi-analytical model of particle acceleration in the symmetric CSF system (with equal velocities of colliding flows) [3]. Here we present a generalized case of this model with arbitrary choice of flows velocities. For detailed discussion of the previous model see [3].

Consider a model describing a population of high energy CR particles with $\Lambda(p) > D_0$ in a vicinity of two approaching shocks with $R_{\rm snr} \gg D_0$ and $R_{\rm sw} \gg D_0$. This model is appropriate for high energy particles (with $E_p \geq 1$ TeV) that are able to cross the distance between the shocks without scattering.

To derive the distribution function at the shock in the case of two colliding shocks we employ a steady-state diffusion-convection equation with the CR particle injection rate $Q(x, p)$:

$$u(x)\frac{\partial f(x,p)}{\partial x} - \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial}{\partial x}f(x,p)\right] = \\ = \frac{p}{3}\frac{du(x)}{dx}\frac{\partial f(x,p)}{\partial p} + Q(x,p)\delta(x), \tag{3}$$

where $D(x, p)$ is the diffusion coefficient, $u(x)$ is the fluid velocity.

Consider points $x = -x_{0_1}$ and $x = x_{0_2}$ to be coordinates of the free escape boundaries (FEB) at the upwards of both the shocks. At these points particles escape from the accelerator into interstellar medium. The shocks collide at $x = 0$. Integrating Eq. 3 from $x = -x_{0_1}$ to $x = x_{0_2}$ and introducing

$$u_{p1} = u_1 - \frac{1}{f_0(p)}\int_{-x_{0_1}}^{0} dx(du/dx)f(x,p)\ , \\ u_{p2} = u_2 - \frac{1}{f_0(p)}\int_{0}^{x_{0_2}} dx(du/dx)f(x,p), \tag{4}$$

where u_i is the fluid velocities immediately upstream (at $x = 0^-$ and $x = 0^+$, $i = 1, 2$), one can evaluate the CR distribution function on the shock:

$$f_0(p) = \frac{3\eta\rho_a(u_1 + u_2)}{8\pi m_p(u_{p1}(p) + u_{p2}(p))}\frac{1}{p^3} \\ -\frac{3}{(u_{p1}(p) + u_{p2}(p))}\int_{p_0}^{p}\frac{\phi_{esc}\,p'^2dp'}{p^3}, \tag{5}$$

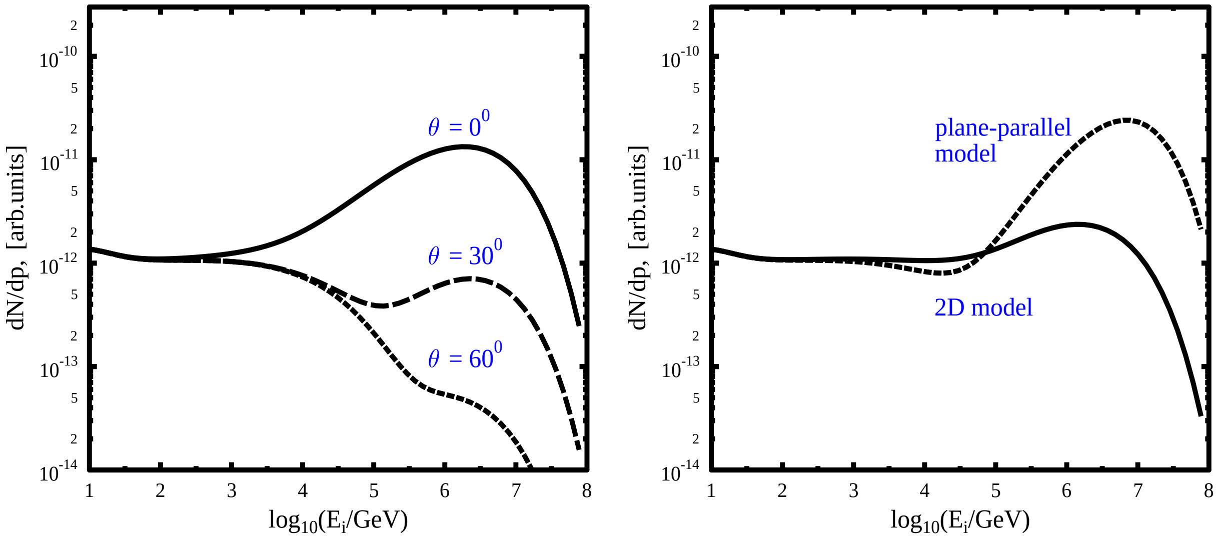

Figure 2. Left: calculated spectra for the different distances from the axis (i.e. for different choices of θ - 0^0, 30^0, 60^0) at time $t - t_0 = 200$ yrs; **right:** average spectrum of the particles *(solid line)* at time $t - t_0 = 200$ yrs comparing to the previously calculated spectrum in the plane-parallel case in model [3] *(dashed line)*

where $\phi_{esc}(p) = -\left(D_1 \frac{\partial f}{\partial x}|_{x01} + D_2 \frac{\partial f}{\partial x}|_{x02}\right)$, ρ_a - is the ambient density, η - is the particle injection rate, m_p - mass of proton. The source point $Q(x,p)$ in the diffusion-convection equation (3) was chosen as follows:

$$Q(x,p) = \frac{\eta n(u_1 + u_2)/2}{4\pi p_{inj}^2} \cdot \delta(p - p_{inj})\delta(x) \tag{6}$$

where p_{inj} - is the injection momentum, $n = \rho_a/m_p$. The function u_p is instrumental to account for the nonlinear modification of the flow due to backreaction of the accelerated particles and it is included into the non-linear calculations (for details see e.g. [7, 8]).

Eq. (5) represents the momentum distribution function for the MHD flow with two colliding shocks with arbitrary chosen velocities. Note, that for every momentum p function $f_0(p)$ is proportional to p^{-3} with correction factor $u_p(p)$. The first term in Eq. (5) reflects CR injection and the second term is due to the escaping flux. The second term is most important for the CR spectral shape at the highest energies and rules out the particle escape and the source contribution to the galactic cosmic rays flux.

4. Calculations

Taking into account expressions (2) and (5) we have calculated SEDs via non-linear time-dependent model [3] of particle acceleration at the CSF system. For each $D(\theta)$ (for $0 < \theta < 90^0$) there were calculated corresponding projections $V_w \cdot cos\theta$ and $V_* \cdot cos\phi$, which are effective velocities of oppositely directed flows for the chosen off-axis distance. For the whole set of pairs of these effective velocities we have calculated SEDs of the accelerated particles using non-linear model described in Section 3.

In figure 2 (left) we present the set of calculated SEDs for the different distances from the axis (i.e. for different choices of θ). Model parameters are the following: SNR velocity $V_{snr} = 5000$ km/s, $V_* = 100$ km/s, $V_{sw} = 2000$ km/s, $D_0 = 0.5$ pc. One can easily see the differences in the spectra: the lower the distance between the shocks (small θ)the better seen a "bump" from the particles accelerated in CSF system at the high energy range. That means that the particles begin to "feel" the second shock and started to be efficiently accelerated by the two-shocks system.

In figure 2 (right) is shown the calculated spectrum of the particles to be compared to the SED for the plane-parallel case in [3]. The presented spectrum is the average of the SEDs calculated for the angles $-90^0 < \theta < 90^0$. Spectra in figure 2 are for the time $t - t_0 = 200$ yrs, pointing the moment when shocks have almost collided. Accounting for 2D geometry results in significant decrease of p_{max} and intensity, comparing with it in the plane-parallel case. The effect of CSF is efficient only when the shocks are close enough ($D_0 << R_{snr}, Rsw$, $dD(\theta)/dR_{curv} << 1$). When one of these condition breaks ($\theta \geq 60^0$) particle experiences only first order Fermi acceleration at the isolated shock and the spectrum tends to the theoretical test-particle limit $dN/dp \propto 1/p^2$ that is typical for the DSA mechanism.

We have splitted the simulation area into 3 arc surfaces: $0^0 - 30^0$, $30^0 - 60^0$, $60^0 - 90^0$, which have produced accelerated particle densities with corresponding weights: 0.84, 0.15 and 0.01. The central region of interaction makes crucial contribution to the overall spectrum while intensity of the further off-axis regions is weak and can be neglected for $\theta \geq 60^0$ with $\approx 1\%$ error in the total spectrum.

5. Conclusion

We have presented the 2D non-linear axisymmetric model of particle acceleration at colliding shocks from supernova remnant and stellar wind from the nearby star. Comparing with the previously developed model we have apply the dissymmetry of the system. This model allows to calculate particle SEDs for arbitrary choice of the distance between colliding shocks. Computer simulations show that the spectra calculated by 2D model have lower intensity and lower p_{max} than it is for the plane-parallel case.

However, the larger velocity of the stellar wind (larger R_0) and the SNR size, the lower the differences in the spectra between plane-parallel and 2D model cases. But accounting for the three-dimensional effects is crucial in the case of relatively small R_0 or R_{snr}, i.e. for the young SNRs and stars with low V_{sw}.

If we assume that SN explodes near the center of the cluster, the ejecta will interact with not just one, but with large number of O-type stars. Assuming that each interaction region leads to a luminosity of 10^{35} erg/s and that there are 100 nearby O-type stars, a luminosity of 10^{37} erg/s is predicted from the whole cluster. This luminosity is well enough to contribute to the galactic CR flux at the high energy range.

6. Acknowledgments

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