Magnetic field amplification and high-energy emission properties of compact galactic clusters

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Abstract. The observed appearance of the high-energy gamma-ray emission from galactic star clusters is determined by the geometry of the cluster and the distribution of the energy sources inside the cluster. A large number of massive stars with strong winds and supernova explosions lead to the formation of multidirectional plasma flows, shocks and strong magnetohydrodynamic turbulence. Magnetic turbulence is the main factor which determine the maximal energies of the accelerated particles and the power of the source. Here we discuss an effect of the efficient magnetic field amplification at the supernova shocks due to the cosmic-ray driven plasma instabilities on the gamma-ray and neutrino fluxes from massive star clusters. We show here that the photon flux attenuation by the $e^{\pm}$ pair production is important for this kind of sources in the photon energy range $10^{15} - 10^{16}$ eV. The ratio of the gamma-ray to the neutrino fluxes is a declining function of the distance to the source at 5-15 kpc and the photon flux can be several times lower than the corresponding neutrino flux from the hadron interactions.

1. Introduction

High-energy emission processes are associated with the most powerful events in the Galaxy. Gamma-ray observations with modern space- and ground-based telescopes have revealed that supernova remnants (SNRs) are the most likely sources of cosmic rays (CRs) at least up to 100 TeV. [1, 2, 3, 4, 5]. The problem of the sources of galactic CRs above 100 TeV is still under debate. Among the others possible sources OB-associations and compact clusters of young massive stars have a potential of CR acceleration well above the PeV energy regime [6, 7, 8]. Moreover the *Fermi* gamma-ray observatory has reported a discovery of an extended gamma-ray source which is associated with the very rich Cygnus OB2 association [9]. Supernovae in compact clusters of young massive stars were argued [8, 10] to be efficient accelerators of CRs above 10 PeV and are the candidate sources to produce a few PeV neutrino events detected by the *Ice Cube* observatory [11].

Efficient particle acceleration in young massive clusters can take place at the SNR and stellar winds shocks, in binary systems at colliding shocks and in collective processes such as multiple shocks interactions. Generation of the magnetohydrodynamic turbulence leads to the fast growth of the magnetic fields in the vicinity of the SNR shocks and stellar winds, that in turn lead to the increasing efficiency of particle acceleration. Non-thermal emission in shell-type structures near molecular clouds may signal about hadronic interactions of the accelerated particles with the interstellar matter (ISM). Modern telescopes such as H.E.S.S., Fermi LAT and Chandra have high sensitivity and resolution that is enough to observe the gamma-ray emission from compact star clusters.

Recently Chandra has detected X-rays emission from supercompact star clusters Arches and Quintuplet which are only 25-30 pc from the galactic center [12]. Fermi LAT and H.E.S.S. have detected hard X-rays and γ-emission from the star cluster Westerlund 1, which is $3.5 - 4$ kpc from the Earth [13, 14].

The progress in numerical simulations of the stellar evolution and the rise of the efficiency of observations provided much better understanding of the physics of star-forming regions. Careful modeling of the emission and acceleration processes requires realistic model that should account for the non-linear feedback of the CRs particles to the acceleration process. In order to consistently describe our non-linear model of high-energy sources in star-forming regions this paper is divided into two parts. The first part is devoted to the description of the semi-analytical model of the magnetic field amplification via CR-ray driven instabilities. This model can be efficiently applied to the numerical simulations of the SNR's shocks and multiple shocks systems in compact star clusters. In the second part we discuss the specific properties of the high-energy gamma-rays and neutrino emission spectra from colliding shock flows systems (CSF) in galactic clusters.

2. The model of magnetic field amplification

Recently E.Amato, P.Blasi and D.Caprioli have developed the non-linear semi-analytical model of the particle acceleration at the SNR shocks, which is useful to calculate feedback effects of the CR particles [15, 16]. We have extended this model to the case of CSF systems that could often occur in star clusters and OB-associations [17, 18].

The model allows to get self-consistently the spectral energy distribution of the accelerated protons $f(x)$ and velocity profile at the shock $u(x)$ for an arbitrary environment parameters (Mach number, the size of the system and density) and diffusion properties of the medium.

Assume that we know $f(x)$ and $u(x)$ from the model above. Let us consider the CRs current, calculated from the proton distribution function, f(x):

$$J_{cr}(x) = -e \int_{p_{min}}^{p_{max}} D(x,p) \frac{\partial f}{\partial x} p^2 dp \tag{1}$$

where $D(x,p)$ - is the diffusion coefficient, p_{min} and p_{max} - are the minimum and the maximum momentum of the particle. The growth rates for the three CR-driven instabilities are derived from the dispersion relation for modes propagating along the mean magnetic field in the magnetized background plasma.

This dispersion relation which includes short-wavelength Bell instability was derived in Bykov et.al. [19]:

$$\begin{aligned} &\omega^2 \mp \omega i k k_c \frac{\alpha_t}{4\pi\rho} \left[\frac{1}{2} \frac{eA(x,k)}{J_{cr}(x)} + \frac{3}{2} \right] - k^2 v_a^2 \pm \\ &\pm k k_c v_a^2 \left(1 + \frac{k_t}{B_{ls}(x,k^*)} \right) \left[\frac{eA(x,k)}{J_{cr}(x)} - 1 \right] = 0, \end{aligned} \tag{2}$$

where ρ is the background plasma density, $v_a = B_{ls}(x,k)/\sqrt{4\pi\rho(x)}$ is the Alfven speed, $k_c = 4\pi |J_{cr}(x)|/(cB_{ls}(x,k))$ is Bell's critical wavenumber at position x in the precursor of the shock, $B_{ls}(x,k)$ is the mean magnetic field, which is defined as the sum of the long-wavelength harmonics and the ambient homogeneous field; $\pm$ signs correspond to the two circularly polarized modes. The value of k^* is determined by the effective resonant condition $k^* c\, p_{min}(x) = eB_{ls}(x,k^*)$; $A(x,k)$, k_t and α_t are defined in [19] and [20].

The relation 2 was obtained from the averaged and linearized momentum equation for the magnetized background plasma (see eq. 11-14 in [19]). Considering only Bell instability we put $k_t = 0$ and $\alpha_t = 0$ in equation 2 and obtain the simplified dispersion relation in the form

$$\omega^2 - k^2 v_a^2 \pm k k_c v_a^2 \left[\frac{eA(x,k)}{J_{cr}(x)} - 1 \right] = 0, \tag{3}$$

The modes growth rates $\Gamma(x,k)$ could be found through the roots of the equation above:

$$\Gamma(x,k) = 2 \cdot Im[\omega(x,k)] \tag{4}$$

where the "2" accounts for the fact that the energy in turbulence is proportional to the square of the amplitude of B.

To calculate the spectral energy density of the magnetic turbulence $W(x,k)$ one should take into account the energy balance equation. Let us consider the energy balance without the flux of the energy through k-space toward larger k and spectral energy of the dissipation rates. Therefore, the energy balance equation is [20]:

$$u(x)\frac{\partial W}{\partial x} + \alpha_g W(x,k)\frac{du(x)}{dx} = \Gamma(x,k)W(x,k) \tag{5}$$

where $\alpha_g = 3/2$.

The equation 5 is solved for magnetic turbulence $W(x,k)$ starting from the following initial condition: $W(x,k) = \frac{B_0^2}{4\pi}\frac{k^{-5/3}}{\int_{k_{min}}^{k_{max}} k^{-5/3}dk}$. Once we have $W(x,k)$ we are able to calculate the effective, self-generated, magnetic field:

$$B_{eff} = \sqrt{4\pi \int_{k_{min}}^{k_{max}} W(x,k')dk'} \tag{6}$$

The presented model of magnetic field calcultion allows to simulate self-consistently non-linear cases of the diffusive shock acceleration (DSA) mechanism. The efficiency of the particle acceleration increases with taking into account feedback effects. Given the large system size $L \approx 3-5$ pc, the high compression ratio of the shock $\sigma = u_1/u_2 \approx 8-10$ and the high velocity of the SNR shock $U_{snr} \approx 5000-7000$ km/s one can get the values of the magnetic field up to $700-800\,\mu G$ through the discussed procedure. Numerical simulations have shown that the maximal energies of the particles accelerated by the SNR's shock with such magnetic fields can reach $Z \cdot (10^{15} - 10^{16})$ eV, where Z is the charge of the particle [21, 22]. For the case of the acceleration by converging flows in the CSF system the maximum can be shifted to $Z \cdot 10^{17}$ eV for a several hundreds years [23].

3. The properties of gamma-ray and neutrino spectra

Magnetic fields determine maximal energies of the accelerated particles and emission properties of the sources as well. In order to get realistic gamma-ray and neutrino emission spectra from compact galactic clusters we have added the discussed magnetic field amplification procedure to the model of the acceleration and emission of CSF systems.

Consider a SNR shell colliding with the stellar wind of a nearby massive star. For a certain period the system will be an efficient accelerator: it will produce high-energy particles bouncing between converging flows. The important features of the particle acceleration in CSFs are: (i) the production of a piece-wise power-law particle distribution with a very hard spectrum of confined particles (with $\Gamma < 2$) at the high-energy end just before a break, and (ii) an increase in the maximum energy of the accelerated particles up to $10^{16} - 10^{17}$ eV. CSF system also increases the acceleration efficiency, compared to that obtained with DSA at an isolated SNR shock of the same speed.

To model the spectra of accelerated particles in CSFs, a non-linear, time-dependent model was constructed in Bykov et al. [17]. From this model with the procedure of magnetic field amplification described in the Section 2 one may calculate particle spectra and escape fluxes [17, 24].

To provide realistic gamma-ray emissivity of the galactic and extragalactic source one should account for the pair-production effect. Energetic photons interact with extragalactic background light (EBL) photons and cosmic microwave background (CMB) radiation field. This interaction leads to the significant suppression of the gamma-ray emission at the highest energy range at the distances ($\geq$ 15 kpc) from the source. Cosmic gamma-gamma opacity strongly depends on the distance to the source of the gamma-ray photon. The optical depth of a gamma-ray photon at observed energy E_γ, emitted by a source at redshift z due to this process is given by [25]:

$$\tau_{\gamma\gamma}(E_\gamma, z) = \int_0^z dz' \frac{dl}{dz'} \int_{-1}^1 d\mu \, \frac{1-\mu}{2} \cdot \\ \cdot \int_{\varepsilon_{th}}^{\infty} d\varepsilon \, n_\varepsilon(\varepsilon, z')(1+z')^3 \sigma_{\gamma\gamma}(\beta', z') \tag{7}$$

where $n_\varepsilon(\varepsilon, z)$ is the number density of background photons with energy ε at redshift z, $\varepsilon_{th} = 2(m_e c^2)^2/E_\gamma(1-\mu)(1+z)$ is the pair-production threshold energy, $\sigma_{\gamma\gamma}(\beta', z')$ – is the gamma-gamma cross-section, $\beta' = (1-\varepsilon_{th}/\varepsilon)^{1/2}$, ε – is the energy of background photon, $\mu = cos\theta$, θ – is the angle between directions of two photons. Gamma-gamma-opacity $\tau_{\gamma\gamma}$ integrated over μ for a wide energy range for the distances 1, 5, 10 and 15 kpc from the Earth is shown on the top of the figure 1. Extragalactic optical-infrared background radiation density n_ε was adopted from [26].

The critical influence of CMB photons occurs at PeV energy range of gamma-rays. Spectrum starts to be totally suppressed when $\tau_{\gamma\gamma} >> 1$, that is the case of extragalactic sources with $d_s \gg 15$ kpc. The EBL from young stars in the cluster would affect the spectrum of the long-distance source only in the 100 GeV – 10 TeV energy regime. This influence is negligible for galactic sources because of the small $\tau_{\gamma\gamma} < 10^{-3}$.

We have calculated neutrino and gamma-ray emission spectra produced by p-p cosmic rays interactions that could come from the one active starforming region with the CSF system. The velocity of the SNR's shock is assumed to be 6000 km/s, the velocity of the stellar wind is 4000 km/s, magnetic field in the vicinity of the SNR's shock is amplified through the model in Section 2 up to 800 μG and the calculated maximal energy of accelerated protons is $2 \cdot 10^{16}$ eV.

For certain galactic sources there would exist a specific influence of gamma-gamma opacity on the resulting spectral shape. In a specific case, when the source is located at $5 \leq d_s \leq 15$ kpc from the Earth and has a spectrum extending to the highest energies $10^{16} - 10^{17}$ eV, one could observe a recess in the gamma spectrum at the PeV energy band. Indeed, $\tau_{\gamma\gamma}$ has a maximum at $\approx 3 \cdot 10^{15}$ eV and then smoothly falls down. If the cut-off of the spectrum is above $\approx 10^{16}$ eV after the "gamma-suppression band" there will exist the second hump in the gamma-ray spectrum (see figure 1, bottom panel). Depending on the spectrum shape the second "hump" can be less or even greater than the first one. Note, that for an extragalactic sources this effect will not appear because of the total suppression of the gamma-ray emission for $E \geq 10^{14}$ eV and very sharp cut-off of the spectrum. Such behavior is also impossible for the closest sources with $d_s \leq 3$ kpc because $\tau_{\gamma\gamma}$ is too small and doesn't affect the PeV gamma-ray spectrum.

It is interesting to note that in this specific case in a little energy band near 10^{15} eV the neutrino flux will exceed corresponding gamma-ray emission up to an order of magnitude.

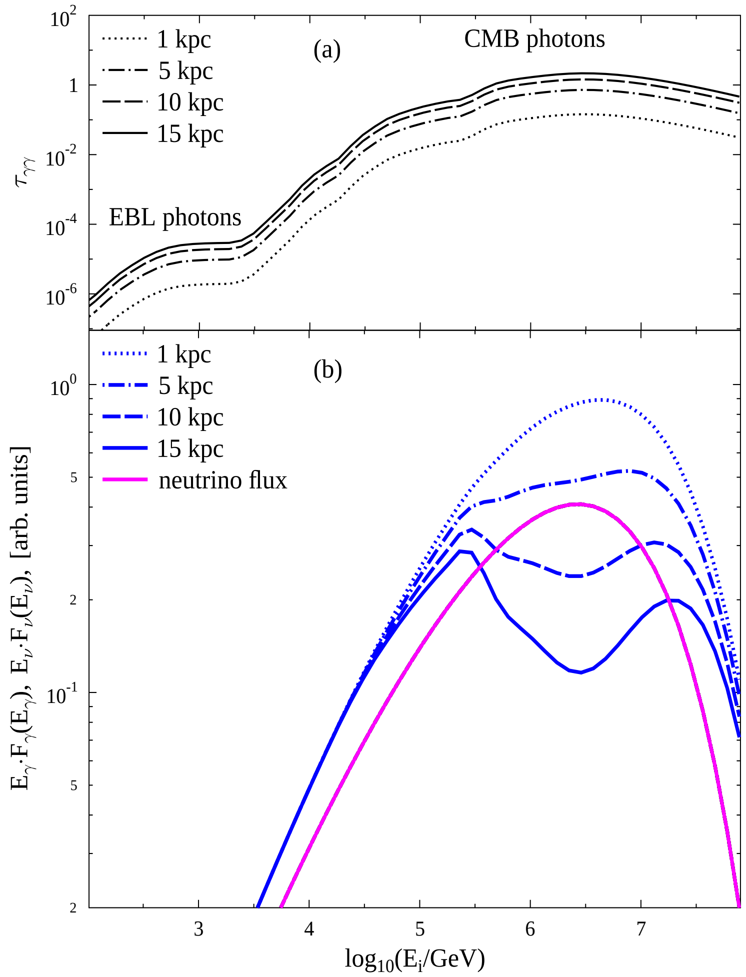

Figure 1. **(a):** the gamma-gamma opacity for a wide energy range integrated over μ for distances 1, 5, 10 and 15 kpc from the Earth; **(b):** the gamma-ray (blue) and neutrino (magenta) high-energy spectra from CSF systems at different distances from the Earth according to the top frame. For a long-distance sources the neutrino flux exceeds corresponding gamma-ray flux at $10^{15} - 10^{16}$ eV.

This feature is extremely important for the physical interpretation of observations of the high-energy emission from galactic clusters and powerful sources which can accelerate particles up to $10^{16} - 10^{17}$ eV.

It should be noted that typical SNRs can hardly produce such a specific spectral shape because of the steep cut-off that usually takes place at $E_c \leq 10^{14}$. Only the source with the hard spectrum at the highest energy range like SNRs of IIb-IIn types and CSF systems could provide specified spectral shape [17, 22]. Future high-energy observations of galactic sources will be able to check this behavior of the high-energy gamma-ray spectrum. Compact massive clusters Arches and Quintuplet situated at approximately 8.5 kpc from the Earth seem to be the most suitable sources to test this model.

4. Conclusion

We have presented the semi-analytical model of the efficient magnetic field amplification in the vicinity of the SNR's shock. Magnetic fields having amplified to 700-800 μG allow protons and heavy nuclei to be accelerated up to $10^{16} - 10^{17}$ eV in compact star clusters. Gamma-ray emission spectra from high-energy sources at 5-15 kpc from the Earth will be strongly affected by gamma-gamma interactions with CMB photons. We have shown that the gamma-ray flux at the energy range of $10^{15} - 10^{16}$ eV demonstrates the non-monotonous behavior and can be several times lower than the corresponding neutrino flux. Future measurements of this difference between gamma-ray and neutrino emission spectra could be an additional tool for the estimation of the distance to the source.

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