Broad-band electromagnetic radiation from microquasars interacting with ISM

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Abstract. Microquasars (MQs) are galactic objects with relativistic jets that constitute a source population which can be responsible for production of a non-negligible fraction of the observed galactic cosmic rays. These relativistic protons, associated with the termination of the jet, interact with the interstellar medium and, at certain surrounding conditions, may lead to production of detectable fluxes of high-energy and very high-energy gamma-rays. This radiation is accompanied by the broad-band emission of secondary electrons from decays of \( \pi^\pm \)-mesons produced through synchrotron, bremsstrahlung and inverse Compton process. The features of broad-band emission initiated by proton-proton (pp) interactions in such a scenario is discussed in the context of the strategy of search for counterparts of high-energy and very high-energy gamma-ray sources in the galactic plane.

INTRODUCTION

In this paper we explore a scenario where microquasar jets (see e.g. [1]) initiate indirect and persistent sources of gamma-rays through interactions of high energy protons, accelerated by jet termination shocks, with high density regions of the interstellar medium (ISM). We study the multiwavelength properties of such sources using a model that calculates the broadband spectrum of the emission coming out from the decay products of pp interactions - \( \pi^0 \)-mesons which lead to direct gamma-ray emission and charged \( \pi^\pm \)-mesons which initiate broad-band emission through synchrotron, inverse Compton and bremsstrahlung losses of secondary electrons. This model takes into account the propagation effects due to the energy dependent diffusion of protons during their travel from the accelerator to the cloud (for more details, see [2]). Below we discuss two cases relevant to both impulsive MQs, i.e. X-ray binaries with transient jets, and continuous MQs, i.e. X-ray binaries with persistent jets.

MQ-CLOUD INTERACTIONS AND PRODUCTION OF GAMMA-RAYS

The jets of MQs end somewhere within the Galaxy, although it is still unclear the way they terminate ([3], [4]). Assuming that the jet contains a significant population of protons and that these protons are (re)accelerated at the terminal part of the
jet to very high energies, interactions between these particles and nearby dense gas clouds leads to the production of neutral and charged pions. Then, $\pi^0$-mesons decay to gamma-ray photons and $\pi^-/\pi^+$-mesons decay to $e^-$ and $e^+$. The secondary electrons radiatively cool due to interactions with the ambient magnetic and radiation fields and gas. Typically, synchrotron emission of these electrons extends from radio frequencies to X-rays and bremsstrahlung leads to high energy radiation from X-rays to TeV gamma-rays (provided that the protons are accelerated at least to energies 100 TeV). One may expect also gamma-rays of inverse Compton origin, but in most cases the contribution of this component is quite small.

Due to energy-dependent propagation effects, the broad-band spectral energy distribution ($\nu F_{\nu}$ or $\epsilon L_\epsilon$) of radiation initiated by protons strongly depends on the age, the temporal character (impulsive or continuous) of the accelerator and the distance between the accelerator (site of the jet termination) and the gas target, e.g. a dense molecular cloud ([5]). The source is expected to be extended with a characteristic size of the dense cloud, persistent and steady (on time scales $\gg 1$ yr). It should be noted that hadronic gamma-rays could be produced at much smaller scales as well, e.g. at interaction of the relativistic jet with the dense wind of the stellar companion ([6]).

RESULTS

Below we present the results of numerical calculations performed for the model parameters summarized in Table 1. The most important parameters are the diffusion coefficient of cosmic rays, assumed in the form $D(E) = 10^{27}(E/1$ GeV)$^{0.5}$ cm$^2$/s, the magnetic field ($B = 5 \times 10^{-4}$ G) in the gamma-ray production region, as well as the acceleration spectrum of protons which is assumed to be a power-law with spectral index $p = 2$ with an exponential cutoff $E_{p,\text{max}} = 10^5$ GeV. Absolute fluxes of radiation are determined by the density of the ambient gas ($n = 10^4$ cm$^{-3}$) and the total energy released in protons in the case of impulsive accelerator, $E_k$, or kinetic energy luminosity in protons in the case of continuous accelerator, $L_k$.

In Figs. 1 and 2, we show the broad-band spectral energy distribution (SED) of radiation of a molecular cloud at different epochs of observations ($t = 0$ corresponds to the start of operation of the accelerator) for the case of impulsive MQ and continuous MQ assuming that the cloud is located at a distance $R = 10$ pc from the accelerator. One can see significant differences between the SEDs corresponding to a sudden release of protons (Fig. 1) and a constant injection of protons (Fig. 2). In particular, in the case of continuous MQ we see a quite narrow distribution of $\pi^0$-decay and synchrotron radiation; this reflects the fact that at any given time and at the fixed distance from the accelerator the protons have a narrow distribution with characteristic energy which decreases with time. In the case of continuous MQ the spectra of protons inside the cloud have broader distributions, especially at later epochs, which transfers to the secondary electromagnetic radiation.

In Figs. 3 and 4, we show the broad-band SEDs at the fixed epoch, $t = 1000$ yr, but at different distances to impulsive and the continuous MQs, respectively (note that the luminosity axis range is not like in Figs. 1 and 2). These figures demonstrate the effect
TABLE 1. The basic model parameters.

| Parameter                                      | Symbol | Value       |
|------------------------------------------------|--------|-------------|
| Diffusion coefficient normalization constant  | $D_{10}$ | $10^{27}$ cm$^2$ s$^{-1}$ |
| Diffusion power-law index                      | $\chi$  | 0.5         |
| ISM medium density                             | $n$    | $0.1$ cm$^{-3}$ |
| High density ISM region/cloud density          | $n_H$  | $10^4$ cm$^{-3}$ |
| Mass of the high density ISM region/cloud      | $M$    | $5 \times 10^3 M_\odot$ |
| Magnetic field within the cloud                | $B$    | $5 \times 10^{-4}$ G |
| IR radiation energy density within the cloud   | $U$    | $10$ eV cm$^{-3}$ |
| Planckian grey body temperature (IR)           | $T$    | $50$ K      |
| Power-law index of the high energy protons     | $p$    | 2           |
| Cut-off energy of the high energy protons      | $E_{p\text{max}}$ | $10^5$ GeV |
| Kinetic energy luminosity for protons in the continuous MQ | $L_k$ | $10^{37}$ erg/s |
| Kinetic energy for protons in the impulsive MQ | $E_k$  | $10^{48}$ erg |

FIGURE 1. The spectral energy distribution (SED) of radiation of a dense cloud under bombardment of protons accelerated at the termination of an impulsive MQ at a distance $R=10$ pc. The results are shown for three different epochs: for 100 yr (curve 1), for 1000 yr (2), and for 10000 yr (3). The model parameters are described in Table 1.

FIGURE 2. The same as in Fig. 1 but for a continuous MQ for the time epochs $t=100$ yr (1), 1000 yr (2), and 10000 yr (3)).
FIGURE 3. The SEDs of radiation of clouds located at three different distances $R = 100$ pc (curve 1), 30 pc (2), and 10 pc (3) from an impulsive MQ at $t=1000$ yr.

FIGURE 4. The same as in Fig. 3 but for a continuous MQ: $R=100$ pc (curve 1), 30 pc (2), and 10 pc (3)).

of propagation, namely how the higher energy particles reach earlier the target, with its impact on the secondary electromagnetic emission.

MQs show variability on different timescales, which implies that proton luminosity should be treated as a mean value. Moreover, these objects often undergo higher states of activity, and therefore a strong outburst with release of large amount of relativistic protons could have happened recently. If so, one should expect a mixture of “old” CRs accumulated over large timescales, typically $10^5 - 10^6$ years, and “young” CRs associated with a recent active phase of the MQ jet. In this case we should expect characteristic spectral features of both persistent and burst type accelerators as demonstrated in Figs. 1 and 2. In Fig. 3 we show an example of such a spectrum initiated by a quasi-continuous accelerator of age $t = 10^5$ year with a mean proton luminosity $10^{37}$ erg/s (dashed lines) on top of the contribution from a recent, 200 year old, burst-like event with total energy release in relativistic protons $10^{48}$ erg. The superposition of these two contributions (solid lines) results in a quite unusual spectral shape over a very large energy region.
FIGURE 5. SED of radiation of a molecular cloud located at a distance of 10 pc from a position of termination of the continuous MQ jet ($t=10^5$ yr) with a recent short-term activity which took place 200 yr ago. The radiation components related to the continuous jet are shown by dashed lines; the components related to the burst type event are shown by dotted lines. The superposition of all radiation components is shown by the solid curve.

from radio to TeV energies. While the TeV gamma-rays and X-rays are associated with interactions of protons produced during the recent burst type event, MeV/GeV gamma-rays and synchrotron radiation at infrared and longer wavelengths are contributed mainly by the “old” proton population produced before the last burst. Detection of such spectra from specific dense regions of the interstellar medium could be an indicator of presence of a nearby persistent accelerator, e.g. a MQ jet, which recently was in an active phase.

While the search of such objects in TeV gamma-rays will constitute an important part of the future surveys of the galactic plane by forthcoming ground-based instruments, it is possible that some such objects are already detected by EGRET. In fact, statistical studies of the unidentified EGRET sources in the galactic plane point to a possible link with high density regions in the inner spiral arms (7). It is likely that the low latitude EGRET sources are grouped in two subpopulations; one formed by variable sources with possible association with MQs (8), and another subpopulation consisting of persistent objects (9). The results of this study show that a part of the persistent EGRET sources also could be (indirectly) related to MQs through termination of their jets in dense environments of the interstellar medium. Feasibility of such a scenario is demonstrated in Fig. 4 where the calculations are compared with the spectrum and luminosity of a “standard” non-variable EGRET source.

CONCLUSIONS

In this work, we have explored the scenario of gamma-ray production due to termination of MQ jets in dense environments of the interstellar medium, e.g. close to massive molecular clouds. The spectrum of broad-band radiation induced by interaction of protons with molecular clouds depends strongly on several parameters, in particular on the age of the accelerator, the distance accelerator–target, and energy dependent diffusion
of protons. In the case of termination of MQ jets with $L_k \sim 10^{37}$ erg/s close to dense clouds ($n \sim 10^4$ cm$^{-3}$) extended secondary synchrotron radiation can be detected from radio to X-ray frequencies. Moreover, gamma-ray emission from GeV to TeV energies could be detected by the new generation of satellite-borne and ground-based gamma-ray instruments like GLAST and HESS.

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