Gamma-rays from active region within stationary inhomogeneous non-local AGN jet

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Abstract: Two stages of non-thermal emission from relativistic jets in active galaxies can be distinguished: a low level persistent emission and a short period flaring emission. It has been recently proposed that both stages are produced in the inner (parsec scale) jet region when electrons are expected to be accelerated to TeV energies. We accept that the low level persistent emission originate in the inhmogeneous, extended, parsec scale jet but the flaring emission is produced by electrons accelerated in small scale localized region of such extended jet. We modify recently developed stationary, non-local, inhomogeneous AGN jet model for the stationary jet emission by introducing a localized flaring active region within the stationary jet which physical parameters differ significantly from those in the extended large scale jet. In such two component inhomogeneous jet model, the radiation produced by electrons in the stationary part of the jet can interact with particles present in the active region of the jet and vice-versa. We investigate how specific emission features depend on the parameters of the active and stationary parts of the extended jet. They can be tested with the future observations with the next generation gamma-ray observatories.

Stationary, non-local, inhomogeneous jet model

In order to describe self-consistently different broad band emission stages (low and high) observed from jets of active galaxies we apply the model for the stationary emission from the jet recently elaborated by Banasiński & Bednarek (2022). In this model, the low level stationary emission, observed from active galaxies, is produced in the whole volume of the extended (parsec scale) jet. We modify this general model by assuming that from time to time within the jet appears an active region. This region moves along the jet with this same velocity but it is characterised by different physical parameters which determine the acceleration process of electrons and their energy losses on different processes. The basic assumptions of the Banasiński & Bednarek model (2022) are summarized below:

The schematic geometry of the stationary jet, with an active region within it, is shown in Fig. 1. The shape of the jet is simplified to a truncated cone with half-opening angle φ. The plasma inside the jet moves with a constant velocity which corresponds to the constant bulk Lorentz factor of the jet Γ_j. The basic parameters of the jet are normalized at the jet base and change with the distance from the jet base with radius R_0. All of the basic jet parameters are shown in the Table 1. The radiation is produced by the relativistic electrons, accelerated continuously along the extended jet, in the synchrotron and the inverse Compton processes. In the plasma rest frame, leptons are distributed isotropically and the spectrum of electrons evolves along the jet due to varying conditions for the acceleration process and energy losses of electrons. Included are losses for adiabatic, synchrotron and inverse compton processes. The evolution of electron's spectrum is described by the kinetic equation i.e. the continuity equation governing the temporal evolution of the electrons distribution which is solved using the numerical method described by Chiaberge & Ghisellini (1999). The density of synchrotron photons locally in the jet, depends on the conditions in the whole jet and the synchrotron photon field at the specific layer in the jet is combined from the synchrotron photons incoming into this layer from both opposite sides i.e backward and forward photons.

The local density of photons is important to obtain the IC losses. We use the generation method to calculate the steady differential spectrum of electrons, N_e, at a specific place. In the first generation, we calculate N_e taking into account only the synchrotron and the adiabatic cooling processes. N_e is obtained by solving the continuity equation. Then, we can calculate the local density of synchrotron photons. In the second generation, we include the IC cooling of electrons. The local density of photons from the first generation is used in the calculations of N_e in the second generation and so on. The third generation of the local density of photons is found to be sufficiently stable. The electrons are considered to be isotropic in the specific place in the jet. However, synchrotron photon field, which is built up from non-locally produced photons coming from different parts of the jet, is highly anisotropic. Therefore, we used the formula for the IC scattering of directed photon beam on the isotropically distributed electrons. Because of anisotropic low energy radiation in the extended jet, the IC process is also strongly anisotropic.

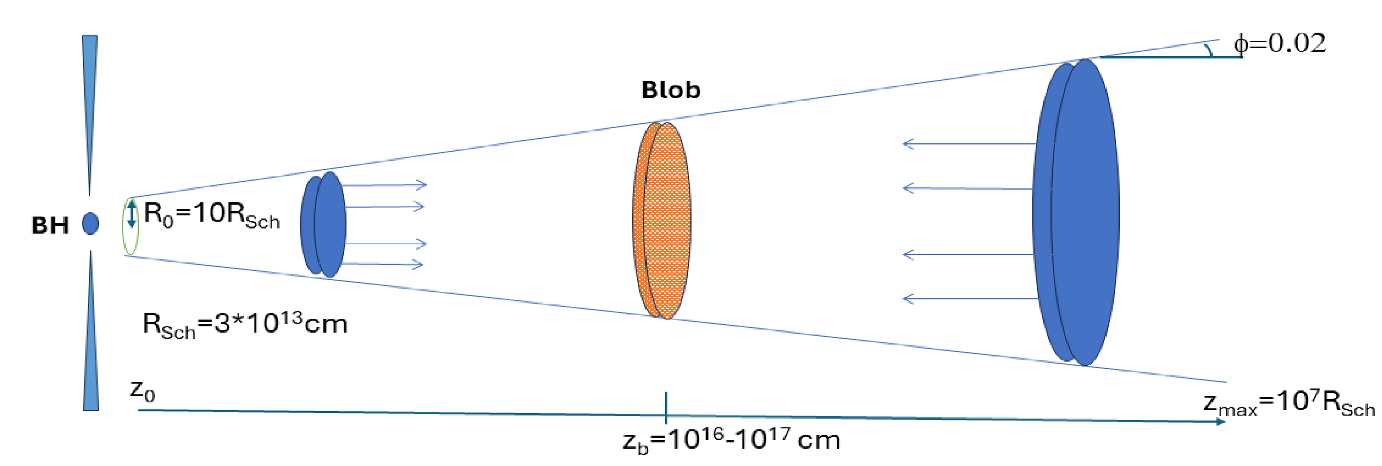

Figure. 1 Schematic view of the jet.

Mass of the black hole M_{BH}	10^8 Mʘ
Bulk Lorentz factor of the jet Γ_j	10
Radius of the jet base R_0	10 R_{Sch}
Half opening angle of the jet φ	0.02 rad
Magnetic field at the jet base B_0	1 G
Power injected in electrons L_{inj}	10^{42} erg/s
Acceleration coefficient η	10^{-6}
Observation angle θ_{obs}	0.1 rad

Table. 1 Basic parameters of the jet.

Gamma-rays from the active region

Discussed above inhomogenous, non-local jet model is able to correctly describe radiation processes within the AGN jet when the flow of plasma through the jet is stationary. This is likely good approximation of the conditions in the jets in the low emission state. However, AGN jets often show variable emission resulting from the presence of localized region in the jet with different conditions. Therefore, we consider the jet model for the high energy processes within the flaring AGN jets in which in addition to the continuous outflow of plasma through the jet we postulate the presence of active regions. These active regions move with the same velocities as the large scale out-flow but are characterised by different physical conditions. For example, such regions can appear as a result of either enhanced number of accelerated electrons or more efficient acceleration of electrons or stronger magnetic field in the limited volume of the jet. In such model, the radiation produced by electrons in the stationary part of the jet can interact with particles present in the active region of the jet and vice-versa.

The considered sizes of the active region, R_b, within the jet which correspond to the range of typical variability time scales of the high energy emission observed from the AGN jets and expected Doppler factors of these jets, i.e. in the range around τ_{AGN} 10^3—10^5 s (C. B. Adams *et al.,* 2022, E. Sobacchi *et al*, 2023) and Doppler factor up to D = 20. Then, we fix the size of the active region (the blob) on $R_b = 3\times10^{16}$ cm at the distance of $z_b = 10^{16}$ cm from the base of the jet. To show the evolution of the emission in time we consider also larger distance $z_b = 10^{17}$ cm .

In Figs. 2-4 are shown the example calculations for Spectral Energy Distributions (SED) for the emission from the inhomogenous, non-local jet alone (solid red line) in comparison with the emission from the jet with active blob (dashed blue line) in two distances of the blob region from the base $z_b = 10^{16}$cm (figs a.) and $z_b = 10^{17}$cm (figs b.). In dotted line it is shown contribution from the blob alone. Three types of blobs are considered with: (i) enhanced magnetic field (one order of magnitude), (ii) enhanced number of accelerated electrons (three times) and (iii) enhanced acceleration coefficient (from 10^{-6} to 10^{-5}).

In the first case (Fig. 2a.) we encounter larger electron energy losses within the blob region which results in amplified synchrotron photon production. Due to larger synchrotron energy losses the electron spectrum in the blob is shifted to lower energies which results in enhanced hard X-ray to soft gamma-ray emission. However this synchrotron emission gives also input into lower energy part of the IC emission being the target for electrons from the whole jet.

In the case of enhanced number of electrons (Fig.3a.) in the whole blob region the emission from the blob is proportionally enhanced and we have these available to be involved in IC process. Acceleration coefficient has impact on the maximum energies of the electrons and thus we observe the synchrotron spectra shifted to higher energies (Fig.4a.). The shift of the IC spectrum is only proportional to the square root of the acceleration coefficient and is limited by the KN effects. All what we observe at larger distance (figures b.) we see that these contribution is getting lower, so we can explain this behaviour as non-stable flare-like feature.

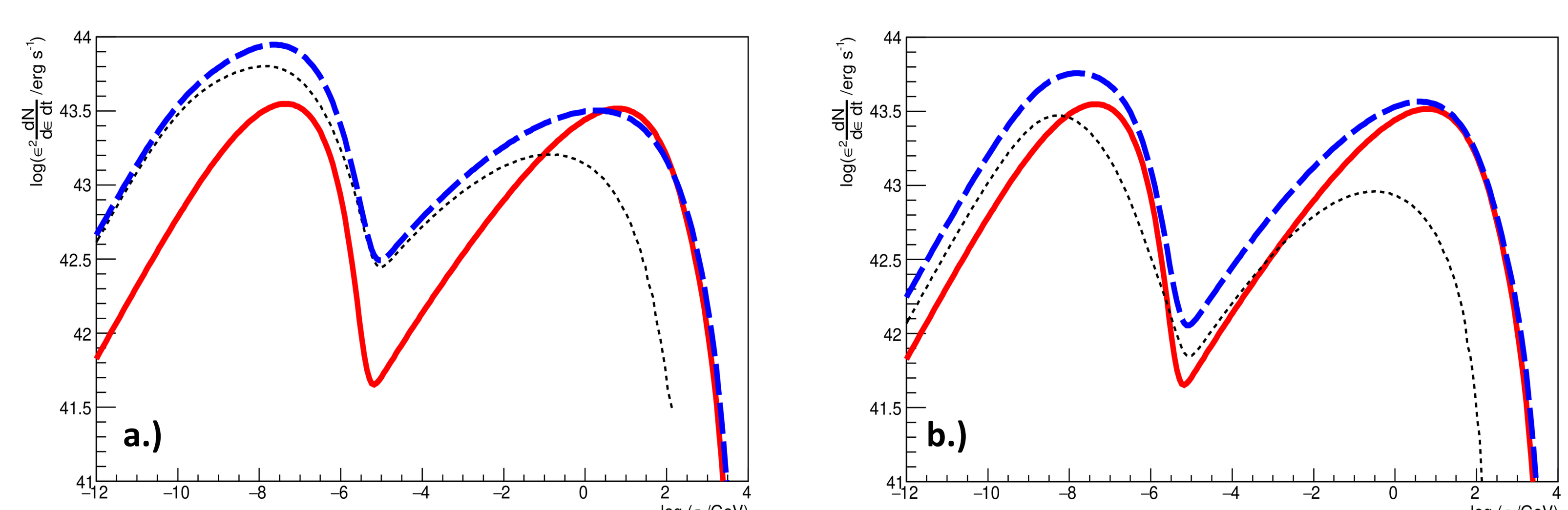

Fig. 2 SEDs for the inhomogenous, non-local jet (solid red line) and for the jet with active blob (dashed blue line) with enhanced magnetic field strength in the blob region, in two distances from the base: $z_b = 10^{16}$cm (a.) and $z_b = 10^{17}$cm (b.). Dotted line shown contribution from the blob alone.

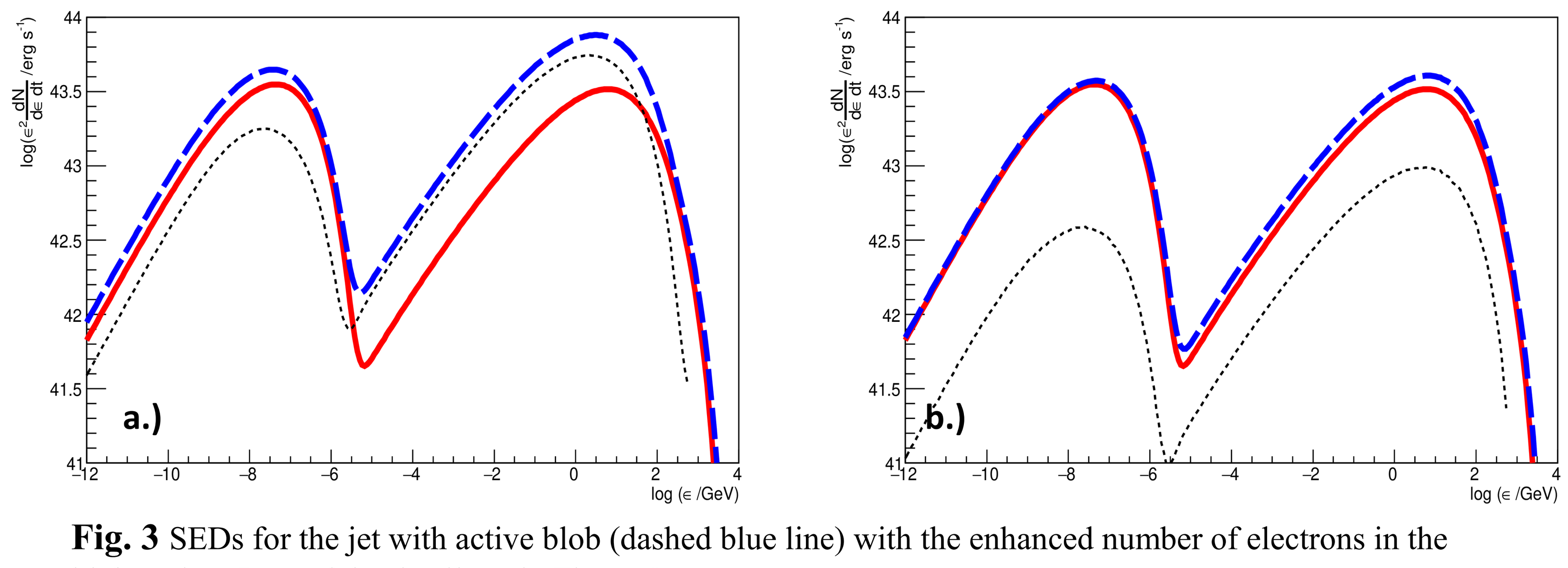

Fig. 3 SEDs for the jet with active blob (dashed blue line) with the enhanced number of electrons in the blob region. Rest of the details as in Figure 2.

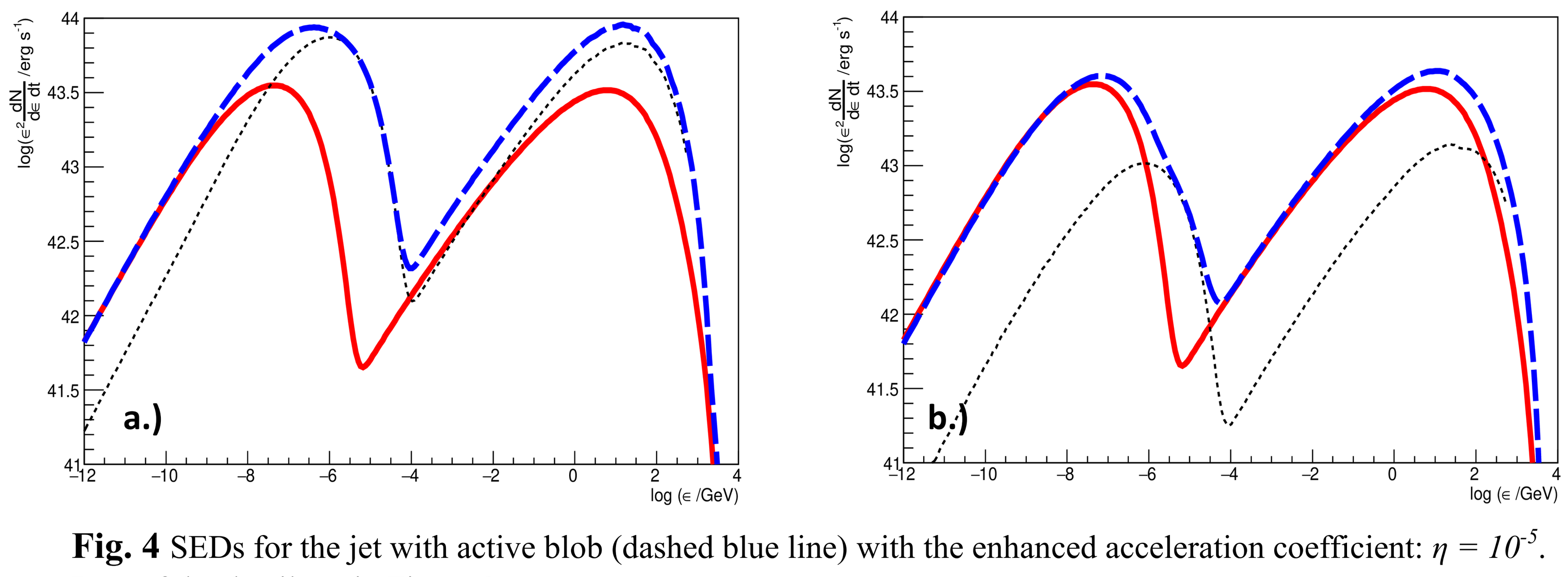

Fig. 4 SEDs for the jet with active blob (dashed blue line) with the enhanced acceleration coefficient: $\eta = 10^{-5}$. Rest of the details as in Figure 2.

Conclusions

We investigate the effect of the active region within stationary, non-local, inhomogeneous jet model for active galaxies. The active region is relatively limited region moving within the stationary jet with this same Lorentz factor but with different physical parameters. We calculate the non-thermal emission from the active region (IC from the interaction of the electrons in the active region with radiation from the whole jet) in the case of: (i) enhanced magnetic field: then, we observe stronger synchrotron emission (radio to X-rays) and stronger IC hard X-ray to soft gamma-ray emission due to effectively cooled electrons in the active region -> orphan synchrotron flares; (ii) enhanced number of electrons in the active region: then, we observe proportionally enhanced emission in the IC part of the spectrum from the active region. The synchrotron emission from the blob is overcomed by the synchrotron emission from the whole jet; (iii) enhanced acceleration coefficient: then, we observe enhanced synchrotron emission shifted proportionally to larger energies and enhanced IC emission shifted proportionally to the square root of the acceleration coefficient -> strong hard X-ray flare;

We conclude that the features of the non-thermal emission from the active regions uniquely indicate on the physical reasons which causes the appearance of the active region (such as the variability in the magnetic field, in the acceleration coefficient, or in the number of relativistic electrons).

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