Modification of the gamma-ray spectra from active galaxies by soft radiation of transiting luminous stars

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Abstract

Gamma-ray emission in active galaxies is expected to originate in a close proximity of the supermassive black hole which is surrounded by a reach cluster of luminous stars. We consider the effects of luminous stars (early type or red supergiant, separate or in binary systems) crossing accidentally the gamma-ray beam close to the observer's line of sight. We show that soft radiation of massive stars can create enough target for transient absorption of the gamma rays in multi-GeV to TeV energy range. We predict characteristic, time-dependent effects on the gamma-ray spectra due to the encounter with stars. As an example, we consider such effects on the spectra observed from a typical blazar, 1ES 1959+650 (in an active state) and also in the case of a radio galaxy M87 (in a low state). Observation of such transient characteristic features in the gamma-ray spectra of blazars and radio galaxies lays within the sensitivity of the future Cherenkov Telescope Array.

1. Introduction

It is supposed that high-energy gamma rays from active galaxies are produced within the inner jet or in the magnetosphere of the supermassive black hole (SMBH). In fact, the TeV gamma-ray emission from blazars can change on a time scale as short as s few minutes (e.g. Mrk 501, see Albert et al. 2007; PKS 2155-304, see Aharonian et al. 2007 or IC 310, see Aleksic et al. 2014), Collimated gamma-ray emission has to propagate through the surrounding region of the SMBH in which many compact objects are expected. The angular extend of such gamma-ray beam in the blazar type of active galaxies is of the order of alpha ~0.1 rad., The beams are typically much broader in radio galaxies, e.g. in Cen A (Tingay et al. 2001, Muller et al. 2014), NGC 1275: Vermeulen et al. 1994), and M87 (Biretta et al. 1999). The beam of energetic gamma rays has to encounter luminous stars that form a quasi-spherical halo around the central super-massive black hole (see Fig. 1a). As a result, a transient, broad absorption feature is expected to appear in the continuum gamma-ray spectrum due to the partial absorption of those gamma rays in the thermal radiation of the star, More details of this work can be found in Bednarek & Sitarek (2021).

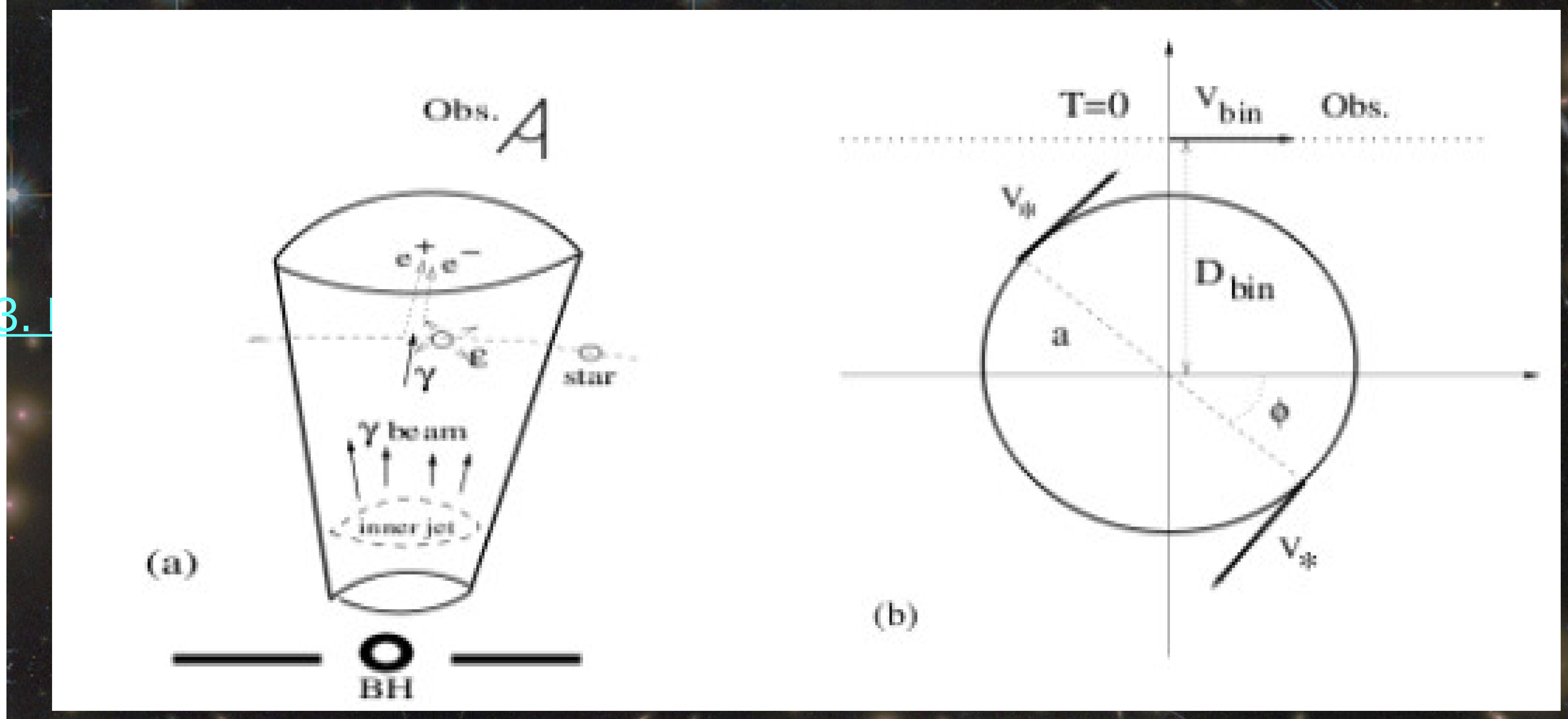

Fig. 1: (a) Schematic representation of the passage of the luminous star through the gamma ray beam in the central region of AGN. (b) The passage of the binary system close to the direction towards the observer in the binary system reference frame. Then, the observer moves with the velocity V_bin with the impact parameter D_{bin}. Two stars with equal masses form the circular binary system with the radius 'a'.
(reproduced from Bednarek & Sitarek 2021)

4. The case of 1ES 1959+650 and M87

We consider the absorption effects on the gamma-ray spectra in the case of two well known active galaxies from which GeV-TeV gamma-ray emission have been reported by the Fermi-LAT and Cherenkov telescopes. The first active galaxy is a BL Lac object: 1ES 1959+650. Recently it was detected in the high state by the *Fermi*-LAT in the multi-GeV energies and by MAGIC in sub-TeV energies (Accciari et al. 2020b). We include the effects of absorption of gamma-ray spectra observed from 1ES 1959+650 in the case of transits of two binary systems (see Fig. 4 on the left). The modifications of the gamma-ray spectrum by the transiting binary system at a specific time before minimum distance between the centre of the binary system and the observer's line of sight are shown for T=-20 – 0 days. We also consider the effect of a transit of the binary system on the spectrum of the well known radio galaxy M87 (detected in a low state, Acciari 2020a). As in the case of 1ES 1959+650, the transits of binary system is considered. Expected modifications of the GeV to TeV gamma-ray spectrum are reported on the right in Fig. 4.

We confront these modified gamma-ray spectra with the sensitivities of the gamma-ray ground-based and space instruments. We used the publicly available instrument response functions (IRF) prod3b-2 of the CTA (Bernlohr et al. 2013). For the stronger source, 1ES1959+650 we use short term (30 min) sensitivity IRF, while for a weaker M87 we use the corresponding mid-term (5 hr) IRF. Moreover, for 1ES1959+650 we also take into account the absorption in the extragalactic background light following Dominguez et al. (2011) model. Using a given flux model, the collection area of the instrument, and its migration matrix, we determine the expected excess rates in each estimated energy bin. With such computed expected number of observed gamma rays, and the rate of background events obtained from CTA IRF, we estimate the expected uncertainty of the reconstructed flux. We consider that the flux can be probed at a given energy if the expected uncertainty is below 50% of the flux (i.e. resulting with $>2\sigma$ point) and the expected number of gamma rays in this energy bin is above 10. In the case of 1ES 1959+650 it is clear that even very short (~30 min) exposure can be used for very accurate probing of the source spectrum and reproducing the absorption feature with high details. In the case of the much weaker In the case of M87, while the intrinsic spectrum can be reconstructed without stellar absorption, the absorption in stellar radiation would render the emission undetectable close to the transit time.

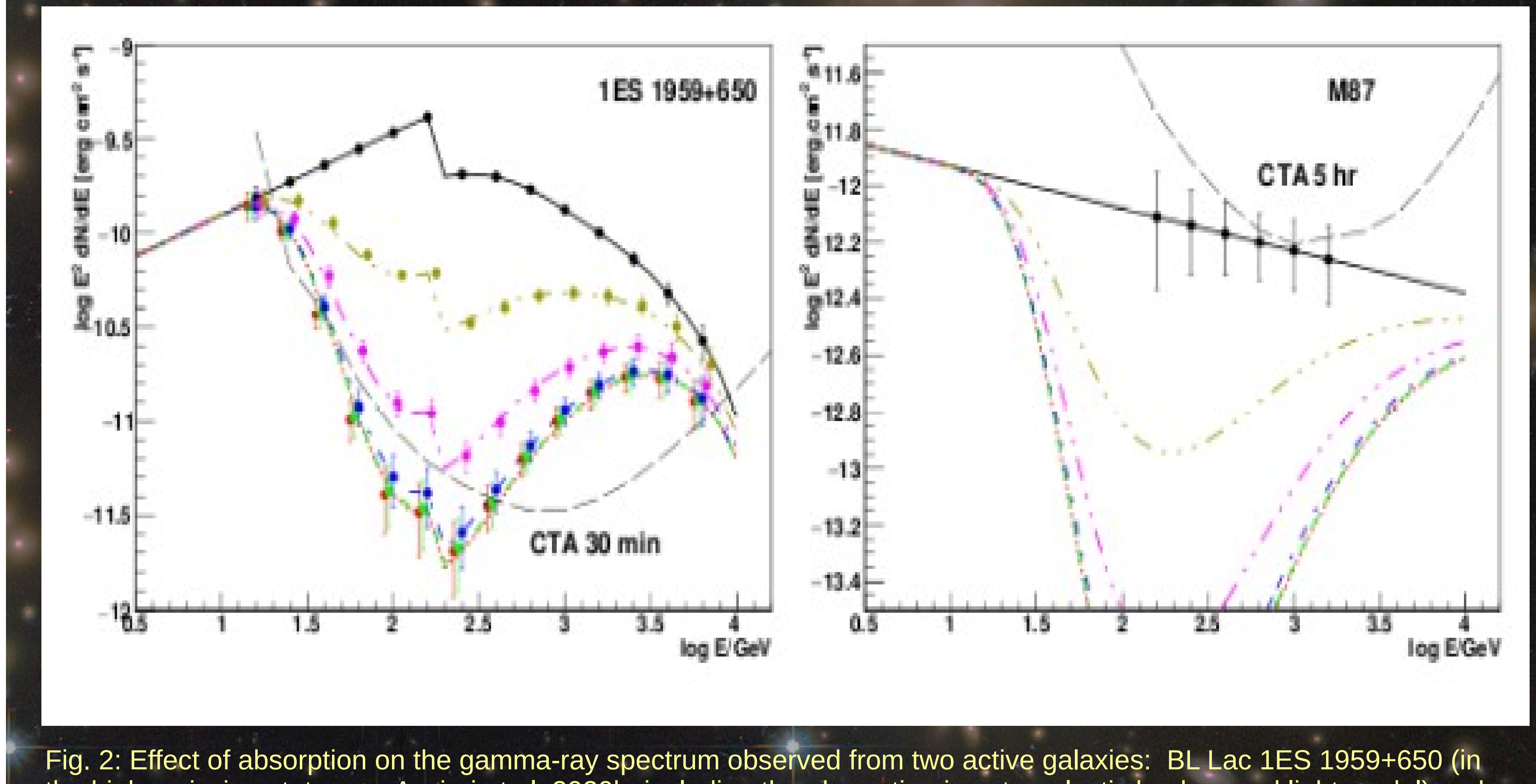

Fig. 2: Effect of absorption on the gamma-ray spectrum observed from two active galaxies: BL Lac 1ES 1959+650 (in the high emission state, see Acciari et al. 2020b, including the absorption in extragalactic background light model) and the radio galaxy M87 (in the low state, see Acciari et al. 2020a). (reproduced from Bednarek & Sitarek 2021)

2. Massive star/relativistic jet incounter model

Many stars can be immersed within the gamma-ray beam (e.g. see Bednarek & Sitarek 2021). The typical parameters of these early type luminous stars are: the surface temperature $T_* = 3x10^4 T_{4.5}$ K and the stellar radius $R_* = 10^{12} R_{12}$ cm. The optical depth, for the gamma ray photons with energies, $E_\gamma \sim 2m_e^2\varepsilon \sim 67/T_{4.5}$ GeV in the case of head on collisions with stellar photons, is $\tau_{\gamma\gamma}(r) \sim D\, n_{ph}\, \sigma_{\gamma\gamma} \sim 110\, R_{12} T_{4.5}^3/r$, where $\sigma_{\gamma\gamma}$ is the cross section for $e^{+/-}$ pair production in collision of two photons, n_{ph} is the density of stellar photons and $r = D/R_*$. This means that gamma rays moving even at large distances from the stellar surface can be absorbed. The duration of the absorption effect on the gamma-ray spectrum can be estimated for the known velocity of the luminous star on a circular orbit around the supermassive black hole. This velocity depends on the distance, $R = 1R_1$ pc, of the star from the SMBH, $v_* \sim 9.4x10^7\, (M_8/R_1)^{1/2}$ cm s^{-1}. where $M_{SMBH} = 10^8 M_8\, M_{sol}$ is the mass of the SMBH. It is evident that the gamma-ray spectrum observed from active galaxies can be sporadically significantly modified in the multi-GeV to sub-TeV gamma-ray energy range.

3. Effects due to passage of a binary system

The absorption effect of the gamma-ray spectrum, in the radiation field of the star, can be evaluated by introducing the so-called "reduction factor" (RF) which determines the ratio of integral gamma-ray photon fluxes in specific range of energies, $E_{min} – E_{max}$, with the effect of the absorption to the non-absorbed (intrinsic) one. The RF factor is defined as:

$$RF_{E_{\rm min}} = \frac{\int_{E_{\rm min}}^{E_{\rm max}} (dN_\gamma/dE_\gamma)\, e^{-\tau} dE_\gamma}{\int_{E_{\rm min}}^{E_{\rm max}} (dN_\gamma/dE_\gamma)\, dE_\gamma}.$$

We assume a differential gamma-ray spectrum of a power-law type with an index of -2. τ is the optical depth for gamma rays in the radiation field of the star. Since half of the stars are expected to form binary systems, we consider the passage of luminous binary stellar system close to the observer's line of sight. The effect of absorption of primary beam of gamma rays can have complicated time dependence since the distances between the observer's line of sight and each of the stars are additionally modulated by the movement of stars within the binary system (see Fig. 1b). For simplicity, we consider that the binary system contains two stars of equal mass. Then, the velocities of specific stars within the binary system are $v_* = (GM_*/4a)^{1/2} \sim 4.1x10^6\, (M_1/a_{13})^{1/2}$ cm s^{-1}, where the radius of the binary system is $a = 10^{13} a_{13}$ cm, and the masses of stars are $M_* = 10M_1$. The cumulative effect of absorption of gamma rays (expressed by the reduction factor RF) in the radiation of stars in the example transiting binary system are shown in Fig. 8 in Bednarek & Sitarek (2021). The simplest binary system case, namely two identical stars with the orbital plane perpendicular to the direction of the gamma-ray beam, is considered. We show the absorption effects for the case of four impact parameters, $D_{bin} = 10^{13}$ cm, $5x10^{12}$ cm, $-5x10^{12}$ cm, and -10^{13} cm, and the initial phase $\phi = 0^o$. The significant reduction of the gamma-ray emission is predicted to occur on a time scale of a few tens of days. However, a strong reduction of the gamma-ray flux, in the form of characteristic two strong absorption dips, is also expected on a time scale of a few days.

We also calculate the effect of absorption on the spectrum of the gamma-ray beam (see Fig. 9 in Bednarek & Sitarek 2021), for the case of the example binary system considered above. Interesting dependence of the spectrum on the transiting time can be observed. The basic feature, softening of the multi-GeV part of the spectrum and hardening of the sub-TeV part of the spectrum, can appear regularly during the transition event close to the minimum approach of the observer's line of sight. For the considered transition event, the effects of absorption are so strong that the gamma-ray flux of the gamma-ray beam can be drastically reduced. It can easily fall below the sensitivity limits of the gamma-ray telescopes in this energy range. Considered here effects should strongly depend on the geometry of the binary system in respect to the observer's line of sight which greatly enhances the possibility of different absorption effects. In general, the plane of the binary system can be inclined at an arbitrary angle to the plane of the sky. The binary system can be formed from two luminous stars which significantly differ in their basic parameters (stellar mass and temperature, binary radius). Therefore, we expect even more complicated structures in the light curve..

5. Discussion and Conclusion

1ES 1959+650 in its high state: *the effect of gamma-ray absorption can be easily observed by the CTA telescopes in the sub-TeV energy range during a few days (see Fig.4). With enough exposure, CTA would be able to observe a clear hardening of the gamma-ray spectrum at sub-TeV energies. Unfortunately, in neither of the two simulated cases Fermi-LAT is sensitive enough to detect such absorption feature.*

M87 in a low state: *CTA would be able to observe a clear hardening of the gamma-ray spectrum at sub-TeV energies.*

The absorption effects will become much more complicated in the case of the binary systems. Even two absorption features might appear in the gamma-rays spectrum observed from active galaxy.

The absorption features can also appear in the case of transiting red hyper- and super-giants. The optical depth becomes of the order of unity already at the distance from the star $D \sim 10R_{RG.}$.

Detection of such transiting events should provide interesting constraints on the parameters of the central stellar cluster in active galaxies such as distribution function of stars, their luminosity function and surface temperatures.

6. Acknowledgement.

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