High Energy Radiation From Collisions of Compact Objects With AGN Jets

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Massive black holes in active galaxies are immersed in huge concentrations of late type stars in the galactic bulges and also early type massive stars in the nuclear stellar clusters which are additionally surrounded by quasi-spherical several kpc scale halos containing from a few hundred up to several thousand globular clusters. It is expected that significant numbers of red giant stars, massive stars and also GCs can collide with a jet of active galaxy. As a result of such collisions, multiple shocks are expected to appear in the jet around these compact objects. Therefore, the plasma in the kpc scale jet can be significantly disturbed. We show that particles can be accelerated on these shocks up to the multi-TeV energies. TeV leptons emit synchrotron radiation, extending up to the X-ray energies, and also comptonize radiation produced in stellar clusters and also the Microwave Background Radiation to TeV γ-ray energies. We show that such non-thermal radiation is likely to be detectable from the intermediate scale jets of the nearby active galaxies. As an example, we calculate the expected non-thermal emission in the X-ray and gamma-ray energies from the nearby radio galaxy Cen A from which a steady gamma-ray emission with the complex spectrum has been recently reported by the *Fermi* and the HESS Observatories.

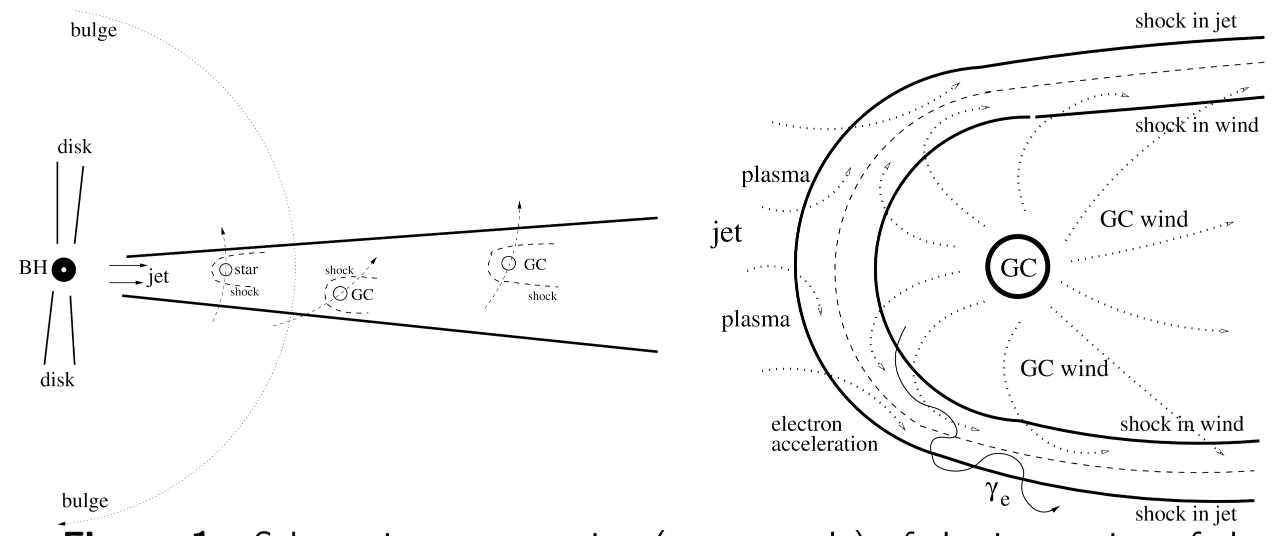

Figure 1. Schematic representation (not to scale) of the interaction of the winds from compact objects (red giants, massive stars, globular clusters) with the plasma of the relativistic jet in active galactic nuclei. On the left: Huge number of stars and GCs create halos around the central engine on the distance scale up to ~kpc and several kpcs, respectively. Some of these objects enter the jet expelled by the central super-massive black hole. On the right: The example case of collision of a GC with a jet. GCs are expected to contain up to a few hundred of millisecond pulsars (MSPs) and a few hundred thousand of normal stars, many of them in the red giant phase. The MSP winds and red giant winds mix efficiently within the cluster producing mixed pulsar/stellar wind from the GC. This GC wind interacts with the jet plasma. As a result, a double shock structure is formed. Acceleration of leptons on the shock in the jet plasma can occur up to multi-TeV energies. These electrons lose energy on the synchrotron process and on the IC scattering of the soft radiation produced by stars in the bulge (at kpc distance scales) and on the Microwave Background Radiation during their propagation along the kpc scale jet.

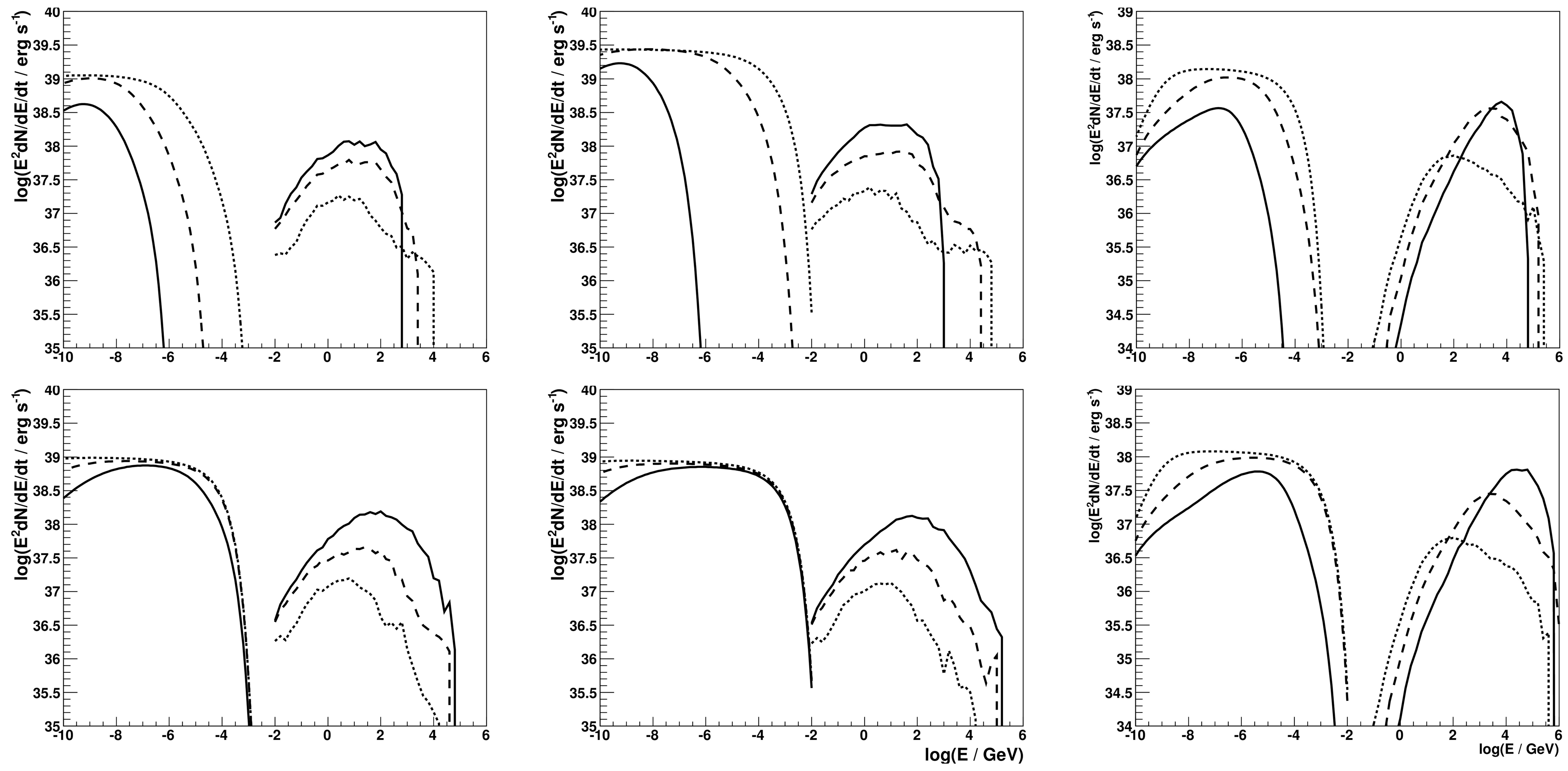

Figure 2. The synchrotron and IC spectra (SED - spectral energy distribution) produced by electrons accelerated at the multiple shocks in the jet plasma around the Red Giants (on the left) and massive stars (in the middle), which entered the jet homogeneously on the range of distances from the base of the jet, $L_{\rm min} = 10$ pc and $L_{\rm max} = 1$ kpc and for the case of GCs (on the right) which entered the jet at the range of distances, $L_{\rm min} = 1$ kpc and $L_{\rm max} = 20$ kpc. The results are shown for the Poynting dominated jet, for the value of magnetization parameter equal to $\mu = 1$ (dotted curves)) and the matter dominated jets described by $\mu = 0.1$ (dashed), and $\mu = 0.01$ (solid). The upper panel shows the spectra for the acceleration parameter of electrons equal to $\xi = 10^{-3}$ and the bottom panel for $\xi = 10^{-2}$. The parameters of the jet are the following $L_{\rm j} = 10^{43}$ erg s$^{\rm 1}$, $\theta = 0.1$ rad. It is assumed that 10^6 red giants and 100 massive stars are present in the jet at the same time. The energy conversion efficiency from the jet to relativisitic leptons is 10%. The other parameters of the stars and the radiation field are reported in the main text.

1. Stars and their clusters around AGNs: The example of Cen A

- Galactic Bulge: stars in the jet $\to\sim 8\times 10^8$ (Wykes et al. 2014), if 10^{-3} of them Red Giants $\approx 10^6$ Red Giants within the jet $\sim$1 kpc.
- Nuclear stellar cluster: $(6-12)\times 10^7$ M$_\odot$ in young stars (Wykes et al. 2014), ~ 100 massive stars within the jet $\sim$1.5 kpc.
- Globular clusters: $\sim$1550 GC around Cen A (Gültekin et al. 2009), a few to several within a jet.

2. Interaction of compact objects with AGN jets

- The jet plasma collide with the stellar winds forming a shock
- The ram pressure of the jet (e.g. Bednarek & Protheroe 1997),

$$P_{\rm j} = \frac{L_{\rm j}}{\pi c\theta^2 l^2} \approx 1.1\times 10^{-9} L_{43}\theta_{-1}^{-2} l_3^{-2} \quad \frac{\rm erg}{\rm cm^3}, \qquad (1)$$

where the power of the jet $L_{\rm j} = 10^{43}L_{43}$ erg s^{-1}, the distance from the base of the jet $l = 1l_3$ kpc, the jet opening angle $\theta\sim 0.1\theta_{-1}$ rad.

- Stars produce winds with pressure,

$$P_{\rm w}^\star = \frac{\dot M_{\rm w} v_{\rm w}}{4\pi R^2} \approx 1.5\times 10^{-13} M_{-7}v_3 R_1^{-2} \quad \frac{\rm erg}{\rm cm^3}, \qquad (2)$$

where the distance from the star is $R = 1R_1$ pc.

- In star/jet collision a shock appears at the distance from star

$$R_{\rm sh}^\star \approx 3.4\times 10^{16}(M_{-7}v_3)^{1/2}\theta_{-1} l_3/L_{43}^{1/2} \quad \rm cm. \qquad (3)$$

- The pressure of the wind (mixed stellar and millisecond pulsar winds) from the globular cluster (Bednarek & Sobczak 2014),

$$P_{\rm w}^{\rm GC} = \frac{\dot M_{\rm GC} v_{\rm w}^{GC}}{4\pi R^2} \approx \frac{9\times 10^{-10}(L_{36}M_{-5})^{1/2}}{R_1^2} \quad \frac{\rm erg}{\rm cm^3}. \qquad (4)$$

where the mass loss rate of stars within a GC is $\dot M_{GC} = 3\times 10^{-5}M_{-5}$ M$_\odot$ yr^{-1} and $L_{\rm MSP} = 3\times 10^{36}L_{36}$ erg s^{-1} is the rotational energy loss rate of all MSPs pulsars.

- The shock in the jet around the GC, $R_{\rm sh}$ at the distance,

$$R_{\rm sh}^{\rm GC} \approx 0.9(L_{36}M_{-5})^{1/4}\theta_{-1} l_3/L_{43}^{1/2} \quad \rm pc. \qquad (5)$$

- The maximum power extracted from the jet, by a star

$$L_{\rm sh}^\star = L_{\rm j}(\frac{R_{\rm sh}^\star}{\theta l})^2 \approx 1.3\times 10^{35} M_{-7}v_3 \quad \frac{\rm erg}{\rm s}. \qquad (6)$$

by a globular cluster (GC),

$$L_{\rm sh}^{\rm GC} = L_{\rm j}(\frac{R_{\rm sh}^{\rm GC}}{\theta l})^2 \approx 8.1\times 10^{38}(L_{36}M_{-5})^{1/2} \quad \frac{\rm erg}{\rm s}. \qquad (7)$$

3. Acceleration of electrons

- The Poynting flux, $L_{\rm P}$, through the jet is a part, μ, of the total jet power, $L_{\rm j}$,

$$L_{\rm P} = \pi r_{\rm in}^2 U_{\rm B} c\Gamma^2 = \mu L_{\rm j} = 10^{43}\mu L_{43} \quad \rm erg\ s^{-1}, \qquad (8)$$

where the inner radius of the jet $r_{\rm in} = 3r_{\rm Sch} = 10^{14}M_8$ cm, the mass of the BH is $M_{\rm BH} = 10^8 M_8$, the energy density of the magnetic field is $U_{\rm B} = B^2/8\pi$, and Γ is the Lorentz factor of the jet.

- The jet can be either Poynting flux dominated (then $\mu\sim 1$) or matter dominated (then $\mu\ll 1$).
- The perpendicular component of the magnetic field in the jet at the distance, l, from its base,

$$B(l) \approx \frac{B_{\rm b} r_{\rm in}}{(r_{\rm in}+\theta l)} \approx 1.7\times 10^{-4}\frac{(\mu L_{43})^{1/2}}{\Gamma\theta_{-1} l_3} \quad \rm Gs. \qquad (9)$$

- The maximum energy of electrons limitted by the synchrotron energy losses are,

$$E_{\rm syn} \approx 55(\frac{\xi}{B})^{1/2} \approx 135\frac{(\xi_{-3}\theta_{-1} l_3\Gamma)^{1/2}}{(\mu L_{43})^{1/4}} \quad \rm TeV. \qquad (10)$$

- The maximum energies of electrons limited by their advection time scale along the shock for stars,

$$E_{\rm adv}^\star \approx 5.2\xi_{-3}(\mu M_{-7}v_3)^{1/2}/(\beta_1\Gamma) \quad \rm TeV, \qquad (11)$$

and for GCs,

$$E_{\rm adv}^{\rm GC} \approx 450\xi_{-3}\mu^{1/2}(L_{36}M_{-5})^{1/4}/(\beta_1\Gamma) \quad \rm TeV. \qquad (12)$$

4. Production of radiation

- Spectrum of accelerated electrons of power law type.
- The maximum energies of electrons limitted by their synchrotron or advection process.
- The minimum energies in stellar collisions, 1 GeV, in GC collisions, 1 TeV.
- Compact objects enter the jet with the rate independent on the distance from the base of the jet.
- Synchrotron and IC spectra from stellar and GC collisions (Fig. 2).

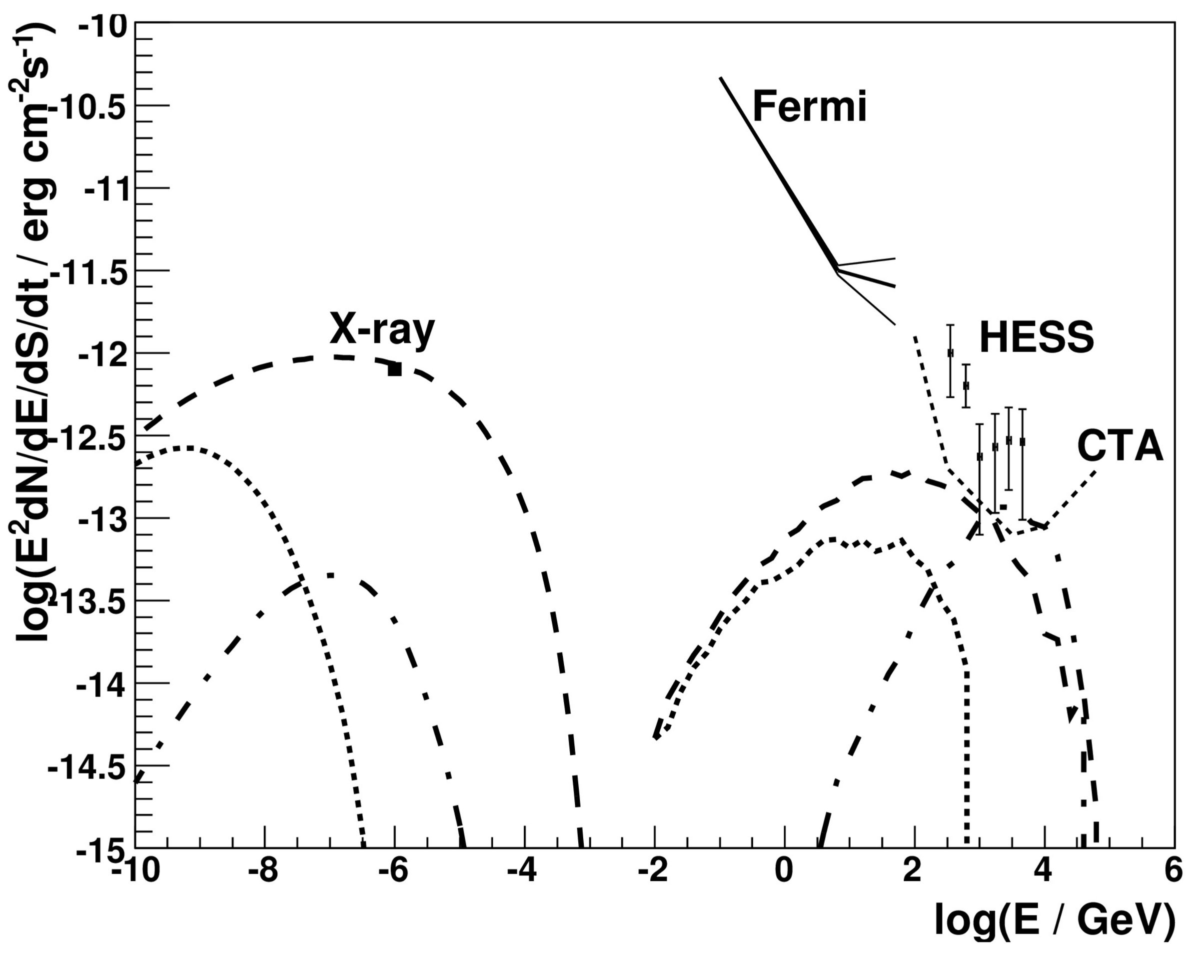

Figure 3. The comparison of the high energy observations of Cen A jet with the calculations of the synchrotron and IC spectra expected from the collisions of GCs and stars with the jet in Cen A. The X-ray emission from the kpc scale jet in Cen A is taken from Hardcastle et al. (2006), the *Fermi* γ-ray spectral measurements are from Sahakyan et al. (2013) and the TeV γ-ray spectrum measured by HESS from Aharonian et al. (2009). The emission expected from the interaction of 10^6 red giants with the jet (dotted curves) and 200 massive stars (dashed curves) is calculated assuming that these stars enter the jet on the distance scale between 10 pc and 1 kpc. The emission from 20 GCs entering the jet on the distance scale between 1 kpc and 20 kpc (dot-dashed curves). The energy conversion efficiency from the shock to

5. Coclusion

- Many compact objects can form a multiple shocks in the jet plasma.
- These shocks can accelerate electrons to multi-TeV energies.
- The TeV γ-ray emission observed from Cen A can originate in the intermediate scale jet.
- Future CTA and GAMMA-400 observations, with their $\sim$arc min resolution, should be able to localize the emission regions in the jet.

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