NON-THERMAL RADIATION FROM COLLISIONS OF COMPACT OBJECTS WITH INTERMEDIATE-Scale JETS IN ACTIVE GALAXIES

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ABSTRACT

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 halos on a scale of several kpc that contain from a few hundred up to several thousand globular clusters (GCs). It is expected that significant numbers of red giant stars, massive stars, and also GCs can move through the jet expelled from the central engine of the active galaxy. We consider collisions of stars from the galactic bulge, nuclear cluster, and GCs with the jet plasma. 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 multi-TeV energies. TeV leptons emit synchrotron radiation, extending up to X-ray energies, and also comptonization radiation produced in a stellar cluster 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 nearby active galaxies for a reasonable number of stars and GCs immersed within the jet. As an example, we calculate the expected non-thermal emission in X-ray and gamma-ray energies from the nearby radio galaxy Cen A, from which steady gamma-ray emission with a complex spectrum has recently been reported by Fermi and the HESS Observatories.

Key words: galaxies: active – galaxies: individual (Centaurus A) – gamma rays: general – globular clusters: general – radiation mechanisms: non-thermal – stars: massive

1. INTRODUCTION

Non-thermal X-ray emission from large-scale jets in nearby radio galaxies of the Fanaroff–Riley class I is expected to be a common feature of such objects, which started with its discovery in two nearby galaxies, Cen A and M87 (Feigelson et al. 1981; Biretta et al. 1991). This X-ray emission smoothly extends up to the radio energy range, supporting the idea of its common origin in the synchrotron process of TeV electrons (Hardcastle et al. 2001). TeV electrons are expected to meet a strong, soft radiation field, produced either in the synchrotron process or by stars in the galactic bulge, and also the microwave background radiation (MBR), from its comptonization to TeV energies (e.g., Stawarz et al. 2003; Hardcastle & Croston 2011). Observations of persistent TeV γ-ray emission from such sources should provide important constraints on high-energy particles in the kpc-scale jets. However, since such electrons have to lose energy on a short timescale, they require an in situ acceleration process. Therefore, efficient acceleration of electrons should occur not only within the inner jet but also in the kpc-scale jets. In fact, the observed X-ray knots in the intermediate-scale jets seem to provide conditions for electron acceleration to TeV energies. These might correspond to shocks formed in collisions of winds from compact objects with the jet plasma (e.g., Hardcastle et al. 2003).

A jet, launched from the vicinity of the central supermassive black hole (SMBH), has to pass through the stellar bulge and globular cluster (GC) halo around the central engine. Since the number of stars in the central stellar cluster is expected to be huge, many of them have to be immersed in the jet plasma. In fact, it has been argued that as a result of the star–jet collisions, stellar winds can introduce a large amount of baryon matter into the jet (e.g., Komissarov 1994; Bowman et al. 1996; Laing & Bridle 2002; Hubbard & Blackman 2006). Shocks formed in collisions of stellar winds with the plasma in the inner jet can also be responsible for the acceleration of electrons, which, comptonizing stellar radiation, might be responsible for the production of γ-ray flares (e.g., Bednarek & Protheroe 1997; Barkov et al. 2010; Bosch-Ramon et al. 2012; Araudo et al. 2013; Wykes et al. 2014). Also, collisions of relativistic jet plasma with dense clouds can lead to γ-ray production (e.g., Blandford & Königl 1979, Dar & Laor 1997; Beall & Bednarek 1999; Purmohammad & Samimi 2001; Araudo et al. 2010; Barkov et al. 2012). These clouds might be fragments of a supernova explosion close to the jet (Blandford & Königl 1979). A large number of objects moving in the galactic bulge are expected to be immersed within the kpc-scale jets.

Galaxies of different types are surrounded by spherical halos of GCs with radii of several kpc. GCs are expected to produce winds that are the products of the mixture of relativistic winds from a large population of millisecond pulsars (MSPs) within the GC and slow baryonic winds from the red giant stellar population within GCs (Bednarek & Sobczak 2014). The mixed millisecond pulsar and stellar winds, expelled from the GC, interact with a relatively rare, relativistic intermediate-scale jet. As a result, a double shock structure forms around the GC. We argue that particles can be accelerated on such shocks to multi-TeV energies. They produce non-thermal radiation by interacting with the magnetic field in the jet (the synchrotron radiation) and with the soft radiation from the galactic bulge on a sub-kpc distance scale, and also with the MBR on a kpc distance scale via the inverse Compton (IC) process.

In this paper we explore the hypothesis that relativistic electrons appear in the intermediate-scale jet as a result of their acceleration on the shocks formed in the collisions of many compact objects (red giants, massive stars, or GCs) with the jet. It is assumed that at distances on the kpc scale jets are already...
non-relativistic and the Doppler boosting effects are small. Under this assumption, we calculate the synchrotron and IC $\gamma$-ray emission produced in the intermediate jet for different parameters of such a scenario. As an example, we show that the high-energy TeV $\gamma$-ray component in the Cen A spectrum, observed by the HESS Collaboration (Aharonian et al. 2009; Sahakyan et al. 2013), might originate within the intermediate-scale jet as a result of the acceleration of electrons in collisions of many compact objects with the jet plasma.

2. STARS AND THEIR CLUSTERS AROUND ACTIVE GALACTIC NUCLEUS (AGN) JETS

Active galaxies are complicated systems, surrounded at a larger scale by a few important elements. The central SMBH, with mass in the range $\sim 10^6 - 10^{10} M_\odot$, is surrounded by the bulge, which has quasi-spherical shape, containing late-type stars within a radius of the order of $\sim$ kpc. The mass of the bulge is related to the mass of the SMBH and its luminosity is of the order of a few tenths of the whole galaxy. Many SMBHs are surrounded by central clusters of luminous and massive stars. Such clusters usually have an extended shape with the main axis in the galactic plane. Their mass and dimension are supposed to be determined by the process of destruction of another galaxy by the massive galaxy harboring the SMBH. Finally, the active galaxy is surrounded by a halo of GCs at distances of several kpc. The number of GCs is related to the mass of the parent galaxy and the mass of the SMBH. The parameters of these stellar clusters around the nucleus of the active galaxy are discussed below.

Nuclear clusters of massive stars are observed not only around SMBHs in massive active galaxies but also in the center of our Galaxy. In the case of our Galaxy such a cluster is relatively small. It has a half-mass radius of $\sim$ pc and a mass of $\sim 2.5 \times 10^7 M_\odot$ (e.g., Schödel et al. 2014). In the case of the nearby active radio galaxy Cen A, the massive stellar cluster was formed around 50–100 Myr ago as a result of a merger process with a gas-rich galaxy. The observed star formation region is centered on the Cen A nucleus. It has visual dimensions of $\sim 8 \times 3$ kpc$^2$ (Neff et al. 2015). The current star formation rate has been estimated as $2 M_\odot$ yr$^{-1}$, which will result in the production of $(6-12) \times 10^7 M_\odot$ of young stars (Wykes et al. 2014). Assuming the standard initial mass function of stars, we estimate the total number of stars with masses above $20 M_\odot$ in the nuclear cluster in Cen A to be $\sim 3 \times 10^5$. A small number of these stars can pass through the jet expelled from the SMBH. A rough estimate of the number of massive O- and WR-type stars, contained within 1.5 kpc from the base of the jet with opening angle of the order of 0.1 rad for the cluster with dimensions mentioned above, is of the order of a hundred. This simple estimate shows that many massive stars can interact with the jet plasma.

Central regions of galaxies are also surrounded by quasi-spherical concentrations of late-type stars (galactic bulges) with typical dimensions of the order of $\sim$ kpc and luminosity of several per cent of the total luminosity of the parent galaxy. Interestingly, the masses of bulges are related to the masses of central black holes (for a review of scaling formulas see, e.g., Czerny & Nikolajuk 2010). In the case of Cen A, the number of bulge stars within the jet has been estimated as $\sim 8 \times 10^8$ (Wykes et al. 2014). If only a small number of these stars are in the red giant phase, of the order of $\sim 10^{-3}$, then the total number of red giants in the Cen A jet can be as large as $\sim 10^9$.

As we mentioned in the Introduction, GCs are also expected to enter the jet from time to time at kpc distances from the base of the jet. In fact, the number of observed (or estimated) GCs around galaxies seems large enough to guarantee encounters with the jet. For example, in the case of our Galaxy more than 150 have been discovered (Harris 1996). Larger galaxies are expected to have more GCs. The Andromeda galaxy is expected to be surrounded by a halo of $\sim 500$ GCs (Barmby & Huchra 2001) but the giant radio galaxy M87 already contains $\sim 13,000$ GCs (McLaughlin et al. 1994). It is shown that in active galaxies containing SMBHs, the number of GCs in the galactic halo is correlated with the mass of the central black hole (e.g., Spitler & Forbes 2009; Burkert & Tremaine 2010; Harris et al. 2014). For example, in the radio galaxy Cen A the number of GCs is estimated as $\sim 1550$ (Gültekin et al. 2009).

3. INTERACTION OF COMPACT OBJECTS WITH AGN JETS

We consider an active galaxy that has a jet propagating from the SMBH. The jet has a conical structure on the intermediate scale. The jet opening angle on a kpc distance scale is expected to be of the order of $\theta \sim 0.1$ rad; see, e.g., observations of the nearby active galaxy Cen A (e.g., Clarke et al. 1992; Hardcastle & Croston 2011). Then, the solid angle subtended by the jet is $\Delta \Omega = 2.5 \times 10^{-3} \theta^2$. Since the number of compact objects surrounding central engine can be very large (see above), many of the late-type stars, massive stars, and GCs can pass through the jet (see Figure 1, left). As we mentioned above, the number of these compact objects is shown to be related to the mass of the central black hole. Therefore, it is expected that very massive black holes, which are on average more luminous, are also surrounded by a larger number of stars and stellar clusters. For example, we estimate the number of GCs within the jets of two well known nearby active galaxies, Cen A and M87, as $\sim 10$ and $\sim 70$ GCs for a jet opening angle equal to 0.15 rad.

The power of jets in nearby radio galaxies is typically of the order of $\sim 10^{43}$ erg s$^{-1}$ (e.g., in Cen A, Wykes et al. 2013). The ram pressure of the jet plasma can be estimated from (e.g., Bednarek & Protheroe 1997)

$$P_j = \frac{L_j}{\pi c \theta^2 l^2} \approx 1.1 \times 10^{-9} L_{43} \theta^{-2} l_3^{-2} \text{erg cm}^{-3},$$

(1)

where the power of the jet is $L_j = 10^{43} L_{43}$ erg s$^{-1}$, the distance from the base of the jet is $l = l_3$ kpc and $c$ is the velocity of light. Compact objects, mentioned above, are also surrounded by winds whose pressure can be balanced by the pressure of the jet plasma. As a result, a double shock structure is expected to appear around the compact objects within the jet, as already discussed in the case of different types of stars. In the case of GCs, hadronic winds from a significant population of red giant stars mix efficiently with the winds from many MSPs within the GC. As a result, the wind emanates from the GC with a power determined by the energy output from the MSP population within the GC. This mixture of red giant/MSP winds collides with the jet’s plasma as shown schematically in Figure 1 (on the right). We argue that particles can be
accelerated at the shocks from the jet site to multi-TeV energies. They produce non-thermal radiation by interacting with the magnetic field in the jet (the synchrotron radiation) and with the soft radiation from the galactic bulge on a kpc distance scale and also with the MBR at distances up to a few tens of kpc (the IC radiation). Below we separately consider the case of collision of a star with the jet and a GC with the jet since these types of object differ significantly in the parameters describing their winds.

3.1. Stars in the Galactic Bulge and Nuclear Stellar Cluster

As we argue above, two different classes of stars are expected to surround the central engine of an active galaxy at distances up to the order of a kpc. They are massive stars from the nuclear stellar cluster and late-type stars (red giants) from the galactic bulge. In fact, collisions of the winds from massive stars with the inner jet plasma in active galaxies, as a possible scenario for acceleration of particles and their radiation, have already been discussed in Bednarek & Protheroe (1997). More recently, the destruction of red giant stars as a result of collisions with the inner jets has been also considered as the mechanism for γ-ray flares (e.g., Barkov et al. 2010; Bosch-Ramon et al. 2012). Such a process of destruction is possible only in the case of very powerful jets and at distances of a few pc from the base of the jet. At large distances, where the pressure of the jet plasma is weak, the winds from the red giant star are strong enough to stop the jet plasma above the red giant surface. As a result, the scenario for collisions of massive stars with jets at intermediate distances from the base of the jet. Recently, the collision of different types of stars with the intermediate-scale jets, as the mechanism for the non-thermal synchrotron emission from jets, has been discussed by Wykes et al. (2014) with application to Cen A.

First, we consider collisions of stars in terms of the parameters of red giant stars. The scenario for collisions of massive stars will be the same in principle. We will comment on possible differences at the end of this section. We assume that a small fraction of the bulge stars, of the order of $10^{-3}$, are in the red giant phase. As an example, we consider red giants with following typical parameters: radius $R_{\text{RG}} = 5 \times 10^{12}$ cm, surface temperature $T_{\text{RG}} = 3700$ K, luminosity $L_{\text{RG}} = 10^3 L_\odot$, mass loss rate $M_\text{w} = 10^{-7} M_\odot$ yr$^{-1}$, and wind velocity $v_w = 3 \times 10^8 v_3$ cm s$^{-1}$. As discussed in Section 2, a large number of red giant stars, of the order of $N_{\text{RG}} = 10^6 N_6$, are expected to be immersed in the intermediate jet of an active galaxy on a distance scale of $\sim 1$ kpc (see estimates for the numbers of bulge stars within the jet in Wykes et al. 2014).

These red giant stars produce stellar winds whose pressure can be estimated from

$$P_w = \frac{M_\text{w} v_w}{4 \pi R^2} \approx 1.6 \times 10^{-13} M_{-7} v_3^{-1} R_{12}^{-3} \text{ erg cm}^{-3},$$

where the distance from the star is $R = 1 R_1$ pc. The stellar wind pressure balances the pressure of the jet plasma at a distance from the stellar surface of (Bednarek & Protheroe 1997)

$$R_\text{sh} \approx 3.6 \times 10^{16} (M_{-7} v_3)^{1/2} \theta_{-1} l_{31}/L_{45}^{1/2} \text{ cm}.$$  

For small distances from the base of the jet, the pressure of the jet might not be balanced by the pressure of the wind of the red giant above its stellar surface. In fact, the shock is above the red giant surface for stars that enter the jet at distances from its base that are larger than

$$l \approx 0.15 L_{45}^{1/2} \left[ \theta_{-1} (M_{-7} v_3)^{1/2} \right] \text{ pc.}$$

For the jet powers as observed in nearby radio galaxies (e.g., Cen A), $L = 10^{43}$ erg s$^{-1}$, this distance scale is only of the order of $l \sim 0.1$ pc. It is much smaller than the radius of the galactic bulge. Therefore, most of the red giants entering the jet in Cen A from its galactic bulge will be surrounded by the shocks at quite some distance from the stellar surface. The atmospheres of these red giants will not suffer direct collisions with the jet plasma as considered by Araudo et al. (2010) and Barkov et al. (2010). Instead, the jet plasma will be stopped at some distance from the red giant surface, creating a shock as
considered by Bednarek & Protheroe (1997) for the case of massive stars entering the inner active galaxies.

The maximum power that can be extracted from the jet by such a shock structure around a single star is estimated as

\[
L_{\text{sh}}^* = L_1 \left( \frac{R_{\text{sh}}}{\theta L} \right)^2 \approx 1.45 \times 10^{35} M_{-7} v_3 \text{ erg s}^{-1}. \tag{5}
\]

Note that this power depends only on the parameters of the red giant star. Since the total number of red giants in the jet can be quite large, significant energy can be extracted from the jet and eventually transferred to relativistic particles in the acceleration mechanism operating in the collision region of the jet and stellar winds.

The parameters of massive stars, which can also enter the jet, are clearly much more extreme than expected for red giants. For example, the terminal velocities of the winds of massive O-type stars can be \(v_\infty \sim (1-3) \times 10^3 \text{ km s}^{-1}\) and the mass loss rates \(M_\infty \sim 10^{-6} M_\odot \text{ yr}^{-1}\); those of WR-type stars can be \(\sim (1-5) \times 10^3 \text{ km s}^{-1}\) with mass loss rates \(\sim (0.8-8) \times 10^{-5} M_\odot \text{ yr}^{-1}\) (Lang 1992). Stars in different phases of evolution can have very large mass loss rates of the order of \(10^{-5}-10^{-2} M_\odot \text{ yr}^{-1}\), e.g., asymptotic giant branch stars or luminous blue variable stars (see Table 1 in Wykes et al. 2014). These massive stars, although more rare than red giants, will produce shocks in jets that are able to extract \(\sim 3-4\) orders of magnitude more energy from the jet plasma than a single red giant.

### 3.2. GCs in the Galactic Halo

As described in Section 2, GCs are expected to create a halo at a distance of several kpc around the central engine of an active galaxy. A substantial number should be submerged in a jet with an opening angle of the order of \(\sim 0.1-0.15 \text{ rad}\). GCs are composed from old low-mass stars of which a significant number, on average about \(\sim 100\), are expected to be in the red giant phase. These red giants are expected to be the main contributors of the mass into the GC through their stellar winds. In fact, the mass loss rate of an isolated red giant is expected to be in the range from \(10^{-9}\) to \(3 \times 10^{-7} M_\odot \text{ yr}^{-1}\) (Boyce et al. 2008; Meszaros et al. 2009). A mass loss rate in the range \(10^{-7}\) to \(3 \times 10^{-5} M_\odot \text{ yr}^{-1}\) is estimated from 100 red giants in a GC. It is expected that a star of a single solar mass should lose about \(\sim 0.3 M_\odot\) during its evolution to a white dwarf (e.g., see discussion in Heyl et al. 2015). Simple estimates of the mass loss rates in a single GC, with a total number of stars equal to \(10^{9}\), give us an average mass loss rate during 10 Gyr equal to \(\sim 3 \times 10^{-5} M_\odot \text{ yr}^{-1}\), consistent with the above estimated value. In our example calculations, we use the mass loss rates of stars in GCs close to this value. On the other hand, GCs contain many millisecond pulsars that have been accelerated to short periods by the transfer of momentum from their stellar companions. These MSPs have typical surface magnetic fields of the order of \(\sim 10^{8} \text{ G}\) and rotational periods of the order of \(\sim 3 \text{ ms}\). The number of such pulsars in a single GC can be of the order of \(\sim 100\), as estimated from their observed \(\gamma\)-ray luminosity (Abdo et al. 2010c). These MSPs lose rotational energy in the form of relativistic pulsar winds that should mix efficiently with slowly moving winds from the red giants (Bednarek & Sobczak 2014). As a result, a baryon-loaded pulsar wind slows down to sub-relativistic velocities. The velocity of the mixed pulsar-stellar wind is estimated to be

\[
v_{\text{w}}^{\text{GC}} = \sqrt{\frac{2L_{\text{MSP}}}{M_{\text{GC}}}} \approx 5.6 \times 10^7 \left( \frac{L_{36}}{M_{-5}} \right)^{1/2} \text{ cm s}^{-1}, \tag{6}
\]

where the mass loss rate of stars within the GC scales with \(M_{\text{GC}} = 3 \times 10^{-5} M_\odot M_\odot \text{ yr}^{-1}\), and \(L_{\text{MSP}} = 3 \times 10^{36} L_{36} \text{ erg s}^{-1}\) is the rotational energy loss rate of all MSPs within the GC.

The pressure of the GC wind is estimated from (Bednarek & Sobczak 2014)

\[
P_{\text{w}}^{\text{GC}} = \frac{M_{\text{GC}} v_{\text{w}}^{\text{GC}}}{4\pi R^2} \approx \frac{9.5 \times 10^{-10} (L_{36} M_{-5})^{1/2}}{R_1^2} \text{ erg cm}^{-3}. \tag{7}
\]

The location of this shock in the jet around the GC, \(R_{\text{sh}}^{\text{GC}}\), can be estimated by comparing the pressure of the wind from the GC with the ram pressure of the jet plasma,

\[
R_{\text{sh}}^{\text{GC}} \approx 0.93 (L_{36} M_{-5})^{1/4} \theta_{-1} l_3 / L_{13}^{1/2} \text{ pc}. \tag{8}
\]

The radius of the shock should be larger than the core radius of the GC. Note that most GCs (\(\sim 90\%\)) in our Galaxy have a core radius below 1 pc (Harris 1996). Therefore, for the parameters considered in this paper we expect that this condition is usually fulfilled for GCs at a distance larger than \(\sim 1 \text{ kpc}\) from the central engine.

The shock structure, formed in collision of the jet with the GC wind, is expected to have a double structure with different conditions on each site (see Figure 1, right). The shock from the jet site is semi-relativistic (the velocity of plasma after the strong shock drops by a factor of three) and has relatively strong magnetic field. On the other hand, the shock in the GC wind is non-relativistic with weak magnetic field. We expect that only the shock in the jet plasma can efficiently accelerate particles to large energies, thus transferring a significant part of the jet power to relativistic electrons. The power that can be extracted by the shock from the jet plasma can be estimated as

\[
L_{\text{sh}}^{\text{GC}} = L_1 \left( \frac{R_{\text{sh}}^{\text{GC}}}{\theta L} \right)^2 \approx 8.6 \times 10^{38} (L_{36} M_{-5})^{1/2} \text{ erg s}^{-1}. \tag{9}
\]

Note that the power estimated above for a single collision of a GC with the jet is clearly larger than in the case of a single collision of a red giant star with the jet, but it becomes of the order of the power expected in the collision of a single massive star with the jet. Therefore, collisions of GCs with jets at distances of a few kpc from the central engine can also be responsible for the formation of powerful shocks in jets at such large distances. In the next section we discuss the possible acceleration of electrons on the shocks formed in collisions of compact objects with jet plasma in relatively nearby active galaxies.

### 4. ACCELERATION OF ELECTRONS

**AT THE SHOCK IN THE JET**

In order to estimate the parameters of particles that could eventually be accelerated in such a scenario, we consider the physical conditions within the jet. The upper limit on the magnetic field at the base of the jet can be estimated by assuming that the Poynting flux \((L_p)\) through the jet is a part
\( \mu \) of the total jet power \( (L_j) \), i.e.,
\[
L_P = \pi r_m^2 U_B E^2 = \mu L_j = 10^{13} \mu L_43 \text{ erg s}^{-1},
\]
for large distances from the base of the jet. In this case, \( B(l) \) does not depend on the mass of the black hole.

We assume that electrons are accelerated at the shock from the site of the jet plasma to energies limited by their synchrotron energy losses. The rate of energy gain by electrons is assumed to be determined by the so-called acceleration coefficient, \( \xi = 10^{-3}\xi_{-3} \).

\[
\dot{E}_{\text{acc}} = \xi E / R_t \approx 9.1 \times 10^9 \xi_{-3} B(l) \text{ eV s}^{-1},
\]

for large distances from the base of the jet. In this case, \( B(l) \) does not depend on the black hole mass.

Note that the advection limit on the energy of electrons mainly depends on the parameters of the stellar wind. On the other hand, the synchrotron limit mainly depends on the parameters of the jet. In general, the advection limit becomes important with respect to the synchrotron limit for the red giant stars in contrast to the case of the massive stars.

Electrons accelerated at the shock around the star can also lose energy efficiently by interaction with the stellar radiation. In order to evaluate the importance of this process we calculate the energy density of stellar photons at the shock region, \( U_s \approx \sigma_{SB} T_s^4 R_s c / [\Gamma M_{L3} v_L] \text{ eV cm}^{-3} \), where the surface temperature of the red giant type star is \( T_s = 3.7 \times 10^5 T_8 \text{K} \) and its radius \( R_s = 5 \times 10^{12} R_{12} \text{ cm} \), and \( \sigma_{SB} \) is the Stefan–Boltzmann constant. On the other hand, energy density of the magnetic field at the shock from the jet site is given by Equation (15). The relative energy losses of electrons on these two processes (in the Thomson regime, i.e., for \( E_e \ll 280 / T_8 \text{ GeV} \)) depends only on the ratio of the energy densities of the radiation and the magnetic field. Therefore, electrons with energies clearly below \( \sim 300 \text{ GeV} \) will lose energy more efficiently by the IC process than by the synchrotron process. However, the energy losses of electrons become comparable for the TeV energies to which these particles are expected to be accelerated at the shocks provided that the jet is Poynting flux-dominated \( (\mu \sim 1) \). Since the winds of massive stars are clearly more extreme than those of red giants, a relatively stronger IC \( \gamma \)-ray emission (with respect to the synchrotron emission) is expected in the case of massive stars within the jets.

The power in relativistic electrons extracted from the shock created by collision of the jet with stellar winds is estimated as
\[
L_e^* = \eta N_e L_{16}^* \approx 1.45 \times 10^{40} \eta_{-1} N_e M_{-7} v_3 \text{ erg s}^{-1},
\]

where \( \eta = 0.1 \eta_{-1} \) is the energy conversion efficiency from the shock to relativistic electrons, and \( N_e = 10^6 N_{16} \) is the number of stars within the jet. The energy conversion efficiency, \( \eta \), is usually expected to be in the range \( \sim 0.1 \sim 0.2 \). The number of massive stars within the jet is expected to be a few orders of magnitude lower than the number of red giants (see Section 2). However, the product of the mass loss rate and the wind velocity of a massive star is typically 3–4 orders of magnitude larger (see Section 3.1). As a result, the power in relativistic electrons accelerated on the shocks formed by the whole population of red giants and massive stars is expected to be at a similar level.
4.2. GCs in the Jet

As above, we constrain the maximum energies of electrons due to their advection along the shock around the GC within the jet. We compare the acceleration timescale, \( \tau_{\text{acc}} \), with \( \tau_{\text{adv}} = 3 R_{\text{GC}}^{\text{avg}} / \dot{E} \). This condition limits energies of electrons to

\[
E_{\text{rad}}^{\text{GC}} \approx 430 \xi_3 \mu_{1/2}^{1/2} (L_{36} M_{-5})^{1/4} / (\beta T) \text{ TeV.} \quad (20)
\]

In general, this limit is less restrictive than the advection limit for stars within the jet, since the shock dimensions around GCs are expected to be clearly larger for typical parameters of the scenario. The synchrotron limit on the acceleration of electrons dominates over the advection limit for the following condition on the least constrained parameter of the model, i.e., the acceleration coefficient should be \( \xi_3 > 0.1 \theta_{-1} \beta_{-3} \Gamma_3^{1/4} \left( L_{36} M_{-5} \right)^{1/6} / \mu_{3/2}^{1/2} \). If the above condition is fulfilled, then we can estimate the characteristic energies of synchrotron photons produced by electrons as \( \varepsilon_{\gamma} \approx m_0 c^2 (B_{0.1} / \dot{E}_{12} m_5) (E_{\text{syn}} / m_5 e^2 c^2)^2 \approx 1.4 \times 10^5 \xi_3 \text{ keV} \), where \( B_{0.1} = 4.4 \times 10^3 \text{ G} \) is the critical magnetic field strength. In the case of Cen A, X-ray emission up to \( \sim 10 \text{ keV} \) is observed (Hardcastle et al. 2006). Therefore, the acceleration coefficient is expected to be at least \( \xi \gtrsim 10^{-4} \).

Electrons with such energies should produce synchrotron emission extending to X-ray energies but also TeV \( \gamma \)-rays by scattering optical radiation produced within the galactic bulge and the MBR.

Let us check whether electrons accelerated at the shock around a GC will manage to cool efficiently by the synchrotron or the IC processes. The electron cooling mean free path by the synchrotron process in the magnetic field of the jet is

\[
\lambda_{\text{syn}} = \frac{E_{\text{syn}}}{\dot{E}_{\text{syn}}} \approx \frac{0.13 (\Gamma_3 \theta_{-1} \beta_{-3})^2}{(\mu L_{43} E_{\text{TeV}})} \text{ kpc.} \quad (21)
\]

The synchrotron cooling process of electrons will occur locally in the jet, provided that the synchrotron mean free path becomes shorter than the characteristic distance scale, which we identify with the distance of the injection place of electrons from the base of the jet, i.e., \( \lambda_{\text{syn}} < l \). The above condition is fulfilled for electrons with energies \( E > 0.1 \theta_{-1} \beta_{-3} (L_{43} \Gamma_3) \text{ TeV} \).

The IC energy losses of electrons can in principle be determined by the soft radiation produced by the GC itself, the galactic bulge thermal radiation, and the MBR. The bulge radiation might play an important role in the inner part of the intermediate-scale jet (i.e., \( \sim \text{kpc} \) scale). The MBR can start to be important in the outer parts of the large-scale jet when the energy density of the magnetic field drops significantly. The energy density of radiation from the GC at the location of the shock can be estimated as \( U_{\text{GC}} = L_{\text{GC}} / 4 \pi c (R_{\text{sh}}^{\text{GC}})^2 \approx 320 L_6 L_{43} / (L_{36} M_{-5})^{1/4} (\theta_{-1} \beta_{-3})^2 \text{ eV cm}^{-3} \), where the optical luminosity of the GC is \( L_{\text{GC}} = 10^9 L_6 L_{43} = 4 \times 10^{36} \text{ erg s}^{-1} \) and \( L_{43} \) is the luminosity of the Sun. The energy density of the bulge radiation is estimated as \( U_{\text{bulge}} = L_{\text{bulge}} / (4 \pi R_{\text{bulge}}^{2} c) \approx 70 L_{11} / R_9^2 \text{ eV cm}^{-3} \), where the bulge luminosity is \( L_{\text{bulge}} = 10^9 L_{11} L_{43} \), and the bulge radius is \( R_{\text{bulge}} = 1 R_9 \text{ kpc} \). The energy density of the MBR is \( U_{\text{MBR}} = 0.25 \text{ eV cm}^{-3} \). The mean free path for electron energy losses by the IC process in the Thomson regime in these radiation fields can be estimated as

\[
\lambda_{\text{IC}}^{\text{T}} = c / E_{\text{IC}} \approx 94 / (E_{\text{TeV}} U_{\text{IC}}) \text{ kpc,} \quad (22)
\]

where \( U_{\text{IC}} = U_{\text{IC}} \text{ eV cm}^{-3} \). We expect that multi-TeV electrons will mainly scatter stellar radiation in the Klein–Nishina (KN) regime but the estimate based on the Thomson cross section allows us to get an impression of the importance of the IC energy losses. The IC losses becomes important when the mean free path of electrons is comparable to the characteristic distance scale on which they propagate. In the case of the radiation field from the GC, \( R_{\text{IC}}^{\text{GC}} \) is always clearly lower than \( \lambda_{\text{IC}}^{\text{T}} \), for reasonable parameters of the scenario. Therefore, energy losses of electrons in the GC radiation can be safely neglected. In the case of the bulge radiation, the mean free path of the IC energy losses can become comparable to the characteristic size of the bulge (of the order of kpc) and also to the mean free path of electrons in the synchrotron process. Therefore, the IC energy losses in the bulge radiation should be taken into account on the kpc distance scale from the base of the jet. The mean free path for the IC energy losses of electrons in the MBR is of the order of \( \sim \text{kpc} \) for electrons with energies of a hundred TeV. Therefore, IC losses of electrons are expected to become important in the outer parts of the jets at distances of several kpc from the base of the jet. Note that the GC halo still extends to such distances.

We conclude that, in fact, electrons can be accelerated to large energies at the shocks formed in collisions of GCs with jet plasma. They should produce synchrotron radiation extending up to the X-ray energy range and also multi-TeV \( \gamma \)-rays by scattering radiation from the galactic bulge and the MBR.

The total power in relativistic electrons accelerated at the shocks around GCs can be estimated as

\[
L_e^{\text{GC}} = \eta_{\text{GC}} L_{\text{sh}}^{\text{GC}} \approx 8.6 \times 10^{38} \eta_{-1} N_{\text{GC}} (L_{36} M_{-5})^{1/2} \text{ erg s}^{-1}, \quad (23)
\]

where the shock power from a single GC is given by Equation (9), and \( N_{\text{GC}} = 10 N_{\text{1}} \) is the number of GCs within the jet.

The maximum energies of electrons are limited in this case by their synchrotron energy losses to values given by Equation (16). For the expected values of the parameters describing the considered scenario, the power in electrons accelerated at the shocks around GCs is estimated to be about an order of magnitude lower than in the case of the shocks around stars. However, electrons accelerated at the shocks around GCs are injected into the jet at much larger distances from its base (i.e., above \( \sim \text{kpc} \)). At these distances the jet magnetic field strength is already weak. Therefore, electrons lose energy relatively more efficiently by the IC process (producing \( \gamma \)-rays) than by the synchrotron process (producing radiation below X-ray energies).

In the next section we perform detailed calculations of the multi-wavelength spectra expected from an intermediate-scale jet assuming that different types of compact objects (red giants, massive stars, GCs) form multiple shocks in the jet plasma. As an example, the parameters of the nearby radio galaxy Cen A are applied.

5. NON-THERMAL RADIATION FROM ELECTRONS

We calculate expected synchrotron and IC spectra produced by electrons accelerated on the fronts of multiple shocks within
the jet for different parameters describing compact objects and the jet content. It is assumed that electrons are accelerated with differential power-law spectra above some minimum energy $E_{\text{min}}$. The spectral index equal to $-2$ is selected for the example calculations as expected in the shock acceleration scenario. The maximum energies of electrons, $E_{\text{max}}$, are determined either by the synchrotron energy losses (Equation (16)) or by the escape from the acceleration region due to the advection of electrons with the jet plasma (Equation (18) or (20)). These electron spectra have been normalized to the power transferred to electrons from the shocks in the jet (see Equations (19) and (23)). In order to obtain the synchrotron and the IC $\gamma$-ray spectra, we inject electrons at different distances from the base of the jet and simulate their propagation in the jet magnetic field and the radiation fields, discussed above, by applying the Monte Carlo method. The KN effect has been taken into account when calculating the IC $\gamma$-ray spectra. In these example calculations, we assume that the jet is semi-relativistic, with apparent velocity equal to $\beta_{\text{app}} = 0.6$, and moves at a relatively large angle to the observer’s line of sight estimated as $\alpha = 50^\circ$ in the case of Cen A. For the above parameters the velocity of the jet is estimated as $\beta \approx 0.52$ and its Lorentz factor as $\Gamma \approx 1.172$. The Doppler factor of the jet in Cen A at the distance of a hundred pc from its base is then estimated as $D = 1/[\Gamma(1 - \beta \cos \alpha)] \approx 1.282$. Note that at kpc distances the jet may significantly decelerate. Therefore, Doppler effects can be negligible in the example of Cen A. Such an assumption clearly simplifies the calculations of non-thermal radiation presented in this paper. The jet has a constant opening angle equal to $\theta = 0.1$ rad and the jet power is $L_J = 10^{43}$ erg s$^{-1}$. For these basic parameters, we investigate the spectra as a function of two other parameters determining the relativistic electrons in the jet—the jet magnetization parameter $\mu$ and the acceleration efficiency of electrons in the jet $\xi$. These two parameters determine the relative part of the energy of relativistic electrons lost by the synchrotron and IC processes.

5.1. Emission from Star–Jet Collisions

The calculations of the IC $\gamma$-ray spectra in the case of collisions of stars with the inner jet (i.e., at distances $<1$ pc) have already been considered by, e.g., Bednarek & Protheroe (1997). In such a case, the shock is located relatively close to the massive companion star and relativistic electrons initiate cascade in the dense stellar radiation field. Calculations of the synchrotron emission from electrons accelerated on the multiple shock structures around the stars in the intermediate-scale jets have been recently considered by Wykes et al. (2014). But no IC $\gamma$-ray emission has been calculated in this model.

We consider the star–jet interaction process at a large distance from the base of the jet. In such a case, the cascade process initiated by electrons accelerated around massive stars is inefficient since the shock is too far from the star. Electrons escape with significant energies from the shock and propagate mainly in the jet volume. At this stage, electrons lose energy by the synchrotron process in the magnetic field of the jet and by the IC process by scattering different radiation fields such as the radiation of compact stars, and diluted radiation from the galactic bulge and the MBR. Electrons propagating outside the bulge, with a typical dimension of $R_{\text{bulge}} = 1$ kpc, will see the radiation field diluted by the factor $(l/R_{\text{bulge}})^2$. In these example calculations we assume that electrons are accelerated on shocks around stars entering the jet uniformly between 10 pc and 1 kpc. Note that in such a case the maximum energies of electrons injected from the shocks into the jet depend on the distance from the base of the jet as given by Equation (16) or (18). The parameters of stars have been fixed at $M_{\star} = 10^{-7} M_\odot$ yr$^{-1}$ and $v_\star = 30$ km s$^{-1}$ (for the red giant stars) and $M_{\star} = 10^{-5} M_\odot$ yr$^{-1}$ and $v_\star = 10^3$ km s$^{-1}$ (for the massive stars).

Results of these example calculations of the synchrotron and IC $\gamma$-ray spectra are shown in Figure 2. We investigate the spectra for the Poynting flux-dominated jets (the magnetization parameter of the jet $\mu = 1$) and for the matter-dominated jets (described by $\mu = 0.1$ and 0.01). We also show the spectra obtained for different values of the acceleration efficiency of electrons $\xi = 10^{-2}$ and $10^{-3}$. In all considered cases, the synchrotron spectra dominate over the IC spectra. As expected, the IC $\gamma$-ray spectra are stronger for less magnetized jets. In the case of red giants, the cut-off in the synchrotron spectrum is determined by the advection timescale of electrons along the shock structure. In contrast, the synchrotron spectrum cuts off independently of the jet magnetization for shocks around massive stars.

5.2. Emission from GC–Jet Collisions

Collisions of GCs with jets in active galaxies have not been considered up to now as a source of disturbances in the jet plasma (shocks) that might be responsible for the acceleration of particles. However, a large number of GCs around active galaxies, and evidence that their numbers are correlated with the mass of the central black hole (Harris et al. 2014), suggest that a significant number of GCs are immersed in the jet. We showed above that shocks around GCs provide conditions for acceleration of electrons to hundreds of TeV. Applying the numerical code for the propagation of electrons in the jet and their radiation described above, we calculate the synchrotron and IC spectra. Since such calculations have not been considered before, we also show the results of calculations of the spectra produced at different distances from the base of the jet. The spectra are investigated as a function of parameters describing the acceleration process of electrons (i.e., the magnetization parameter of the jet $\mu$ and the acceleration efficiency of electrons $\xi$). Electrons are injected at a fixed distance from the base of the jet and, after leaving the shock, they are frozen in the jet plasma. In such a case, the synchrotron energy losses of electrons are determined by the profile of the magnetic field along the jet (see Equation (12)). On the other hand, these electrons also comptonize radiation from the galactic bulge (with photon density dropping with the distance along the jet) and the MBR. Note that electrons are accelerated to larger energies farther along the jet. As in the case of collisions of stars with the jet, we assume that electrons reach the power-law spectrum extending up to the maximum energies described above. In the case of GCs, the minimum energy of electrons is fixed at 1 TeV, which corresponds to the characteristic energy of leptons injected by the MSPs into the mixed pulsar/stellar wind from the GC.

In the example calculations of the synchrotron and the IC spectra, we apply the parameters derived for the nearby radio galaxy Cen A: mass of the black hole $M_{\bullet} = 0.5$, jet power $L_{\text{jet}} = 1$, jet opening angle $\theta_{\text{jet}} = 1$, jet velocity $\beta = 0.5$ ($\Gamma \approx 1.15 \sim 1$), and the parameters typical for GCs: GC stellar luminosity $L_\star = 1$, power supplied by MSPs $L_{\text{MSP}} = 3$, mass loss rate of red giant stars $M_{\text{MSP}} = 3$, and the parameters of
the host galaxy bulge: bulge stellar luminosity $L_{\text{bulge}} = 10^{11}L_{\odot}$, bulge radius $R_3 = 1$. The acceleration coefficient is taken to be $\xi_3 = 1$ in order to be consistent with the observations of the non-thermal X-ray emission from the jet. The radius of the shock around the GC is then $R_{sh} \approx 2.7l_3$ pc, the magnetic field strength along the jet is $B(r) \approx 5.6 \times 10^{-5}\mu^{1/2}/l_3$ G, the maximum energies of electrons due to synchrotron energy losses are $E_{\text{syn}} \approx 170(l_3/\mu)^{1/2}$ TeV, and the maximum energies of electrons due to advection from the shock are $E_{\text{adv}} \approx 1800\mu^{1/2}$ TeV. The comparison of these two last limits gives us the range of distances for which the synchrotron limit is more restrictive, i.e., $l_3 < 100\mu^{1/2}$. We conclude that the maximum electron energies are always limited by synchrotron losses in the case of a Poynting-dominated jet. They are limited by the advection process in the case of a matter-dominated jet with $\mu = 0.01$. For $\mu = 0.1$ the acceleration process of electrons is limited by the synchrotron energy losses in the inner part of the jet, i.e., below $l_3 = 1$, but by the advection process in the outer parts of the jet. The mean free paths of electrons are $\lambda_{\text{syn}} \approx 240l_3^{1/2}/(\mu E_{\text{TeV}})$ pc for the synchrotron process, $\lambda_{\text{IC}}^{\text{bulge}} \approx 1.3/E_{\text{TeV}}$ kpc for the IC scattering of bulge radiation, and $\lambda_{\text{IC}}^{\text{MBR}} \approx 380/E_{\text{TeV}}$ kpc for the IC scattering of the MBR. The characteristic distance scales for IC energy losses of electrons on the border between the Thomson (T) and the KN regimes in the bulge radiation are comparable to the bulge dimension. These distance scales for IC energy losses of electrons with TeV energies in the MBR are comparable to the dimensions of jets in AGNs.

In Figure 3, we show the synchrotron and the IC spectra for different distances from the base of the jet, $l = 1, 3$, and 10 kpc.

The Poynting flux-dominated jets ($\mu = 1$) and the matter-dominated jets ($\mu = 0.1$ and 0.01) are considered. In the former case, the IC spectra are at a much lower level than the synchrotron spectra, especially at lower distances from the base of the jet. On the other hand, the IC spectra start to dominate over synchrotron spectra at larger distances from the base of the jet in the case of matter-dominated jets defined by the magnetization parameter $\mu \sim 0.01$. Therefore, most of the energy of relativistic electrons can be transferred to TeV $\gamma$-rays in a jet at distances of a few kpc from its base. The synchrotron spectra produced in the jet by these electrons clearly extend up to the X-ray energy range, even for the advection-dominated acceleration process of electrons, for the range of parameters considered, $0.01 < \mu < 1$ and $10^{-3} < \xi < 10^{-2}$.

The synchrotron and IC spectra produced by electrons accelerated at shocks formed by GCs entering the jet at a range of distances from its base between 1 and 20 kpc are shown in Figure 4. It is assumed that GCs enter the jet homogeneously over such a range of distances and eject electrons with the spectra and powers as described above. The results are shown for the parameters as in previous figures. It is clear that in the case of the matter-dominated jets the level of TeV $\gamma$-ray emission is comparable to the level of synchrotron X-ray emission. In this case, the $\gamma$-ray spectra peak at multi-TeV energies and the synchrotron spectra extend above $\sim 10$ keV. However, in the case of Poynting-dominated jets, the synchrotron emission clearly dominates over the TeV $\gamma$-ray emission. The $\gamma$-ray luminosity is expected to be about an order of magnitude below the X-ray luminosity and the $\gamma$-ray spectra peak at GeV energies.

The parameters of the jet are the following:

- $L_{\text{jet}} = 10^{43} \text{erg s}^{-1}$, $\theta = 0.1$ 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 relativistic leptons is 10%.
- The other parameters of the stars and the radiation field are reported in the main text.
We show that in the case of matter-dominated jet models, the collisions of GCs with the kpc-scale jets can be responsible for the detectable synchrotron X-ray emission and also for the TeV γ-ray emission. The relative levels of the emission in these two energy ranges should provide important constraints on the content of jets at kpc-scale distances. Note that in the matter-dominated jets the maximum energies of accelerated electrons are determined by their escape from the shock region due to the advection process. These electrons are not completely cooled when propagating in the jet on the distance scale of 20 kpc considered in the paper. Therefore, the IC spectra are so hard below the peak at TeV energies. The lower energy electrons are cooled on a much longer distance scale. They should produce steeper spectra on similar angular scales in the case of distant AGNs, for which the contribution to the IC spectrum comes from a more extended part of the jet. Therefore, such hard spectra are only expected from the intermediate-scale jets in nearby AGNs such as Cen A, for which the distance of 20 kpc corresponds to an angular size of the source of several arcminutes. We considered only semi-relativistic jets, as observed in nearby AGNs. In the case of relativistic jets, expected in distant AGNs, these maximum energies of accelerated electrons are expected to be lower (see Equation (20)). Therefore, the spectra may not extend to ∼10 TeV. These spectra are not expected to be hard enough to provide interesting constraints on the extragalactic background light.

6. APPLICATION TO CENTAURUS A

Centaurus A is the closest radio galaxy to us (distance $3.8 \pm 0.1$ Mpc) and associated with the elliptical galaxy NGC 5128 (Harris et al. 2010). The SMBH in Cen A has a mass estimated as $M_{\text{BH}} = (5.5 \pm 3.0) \times 10^7 M_\odot$ (Cappellari et al. 2015).
Two jets, clearly asymmetric on a kpc scale, are observed in Cen A. The viewing angle of the jet has been estimated as $\approx 50^\circ$ (Tingay et al. 1998; Hardcastle et al. 2003). The projected speed of the jet on a distance scale of a hundred pc has been measured as $0.5c$ (Hardcastle et al. 2003). The power of the jet has been estimated as $P_j \sim 10^{41}$ erg s$^{-1}$ (Wykes et al. 2013).

Due to its proximity, X-ray emission is clearly seen from the kpc-scale jet in Cen A (Feigelson et al. 1981). At distances between $\sim 1$–3 kpc, Chandra observations (0.4–2.5 keV energy range) show that the diffusive X-ray emission dominates over X-ray emission from the knots. This X-ray emission has been interpreted as being due to the synchrotron process (Hardcastle et al. 2006). Such synchrotron radiation requires the presence of TeV electrons in the kpc-scale jet. They have to be accelerated close to the radiation site due to short energy loss timescales. Recently, a pointlike $\gamma$-ray source with a power-law spectrum (spectral index $\sim 2.7$) extending to $\sim 2$–3 GeV has been detected by the Fermi satellite from the core of Cen A (Abdo et al. 2010a). Analysis of the four years of the Fermi data shows that $\gamma$-ray emission extends up to $\sim 50$ GeV. However, the spectrum flattens above $\sim 4$ GeV (Sahakyan et al. 2013). The spectral index changes from $2.74 \pm 0.03$ below 4 GeV to $2.09 \pm 0.20$ at higher energies. This flattening of the $\gamma$-ray spectrum is consistent with the detection of the TeV source toward Cen A by the HESS Collaboration (Aharonian et al. 2009). It suggests that the TeV and hard GeV emission might originate in the same mechanism. The lower energy points of these TeV observations (>$250$ GeV) link nicely to the high-energy component detected by Fermi but the spectral index of the TeV emission is again better described by a steep spectrum (spectral index $2.73 \pm 0.05$ at $0.2\gamma_{\text{max}}$, see Aharonian et al. 2009). Such curious spectral behavior, lack of detected clear variability, and pure angular resolution of $\gamma$-ray observations suggest the involvement of at least two radiation processes or emission regions (Sahakyan et al. 2013). Due to the large angular extent of the Cen A jets on the sky (of the order of $\sim 10^\circ$), the Fermi observatory was also able to discover GeV $\gamma$-ray emission from the regions of the giant radio lobes formed in collisions of jets with the intergalactic medium (Abdo et al. 2010b). All these high-energy observations show that the high-energy processes are characteristic not only of the direct vicinity of the SMBH but also of the large-scale jets. We wonder whether the highest energy component (at $\sim 1$ TeV), observed from Cen A by the HESS Collaboration, can originate in the kpc-scale jet due to the acceleration of electrons on the shocks in the jet that are produced in the collisions of compact objects (stars, GCs) with the jet plasma.

In order to test this hypothesis, we performed calculations of the synchrotron and the IC spectra expected in terms of the above collision model of jet and compact objects, applying the known parameters of the jet and the surrounding medium of Cen A. The results of calculations are compared with the observed high-energy spectrum from Cen A (Figure 5). In this figure the X-ray spectrum represents emission from the kpc-scale jet (Hardcastle et al. 2006). The Fermi spectrum comes from the central part of the galaxy harboring Cen A (Sahakyan et al. 2013). The origin and location of this steady spectral component are at present unknown due to the pure angular resolution of the Fermi-LAT telescope. Finally, the data points show the measurements of the TeV $\gamma$-ray emission from the

![Figure 5. Comparison of the high-energy observations of the 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 $\gamma$-ray spectral measurements are from Sahakyan et al. (2013), and the TeV $\gamma$-ray spectrum measured by HESS is 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 by 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 $1$ and $20$ kpc is shown by dotted-dashed curves. The energy conversion efficiency from the shock to leptons is assumed to be $10\%$. The sensitivity of the CTA is marked by the thin dotted curve.

Cen A inner/intermediate-scale jet. We assumed that the red giant stars and massive stars enter the jet uniformly at distances between $10$ pc and $1$ kpc from the base of the jet. Electrons are accelerated at the shocks with an energy conversion efficiency of $\eta = 10\%$. The spectra are calculated for the presence of $10^6$ red giants (dotted curves) and $200$ massive stars (dashed curves) within the jet. The example parameters of these stars are described in Section 5.1. For the considered parameters of the acceleration model ($\mu = 0.01$, $\xi = 10^{-3}$), the emission from electrons accelerated on the shock around red giants is not expected to contribute significantly to the high-energy spectrum observed from Cen A. On the other hand, about a hundred massive stars in the jet can produce synchrotron emission at the level observed from the jet of Cen A. The accompanying $\gamma$-ray emission, from the componization of background radiation by these same electrons, is at the level of the TeV $\gamma$-ray emission reported by HESS from Cen A. We also show the synchrotron and IC spectra produced in collisions of $20$ GCs with the jet at larger distances (dotted curves) for these same parameters of the jet. The synchrotron emission is not expected to contribute significantly to the observed X-ray spectrum. However, the IC $\gamma$-ray emission peaks at TeV energies. The cumulative $\gamma$-ray spectrum from collisions of massive stars and GCs with the jet is clearly consistent with the level of TeV $\gamma$-ray emission observed by HESS. Therefore, such a model might be responsible for the highest energy $\gamma$-ray component observed from Cen A. If the jet in Cen A still moves with a velocity of the order of $0.5c$ over kpc distances, then the calculated spectra (in Figure 5) should be enhanced by a factor of $D^2 \sim 2.7$. As a result, our estimates of the number of compact objects within the jet should be reduced by this factor.

We conclude that the steady TeV $\gamma$-ray emission observed from the central part of the radio galaxy Cen A can originate in the kpc-scale jet. This emission (or at least a part of it) should
be steady, independent of the activity state of the inner jet. Since the expected emission is above the level of sensitivity of the future Cherenkov Telescope Array (CTA), the question of the existence of low-level persistent emission from the intermediate-scale jet in Cen A should be definitively answered in the coming years.

7. CONCLUSIONS

We propose that the compact object/jet collision model can be responsible for the non-thermal emission from the intermediate-scale jets observed in nearby radio galaxies. We consider collisions of different types of objects, starting from the red giant stars from the galactic bulge, through the massive stars from the nuclear central cluster, and finishing with the GCs in the galactic halo. Collisions produce multiple shocks in the jet, on which leptons can be accelerated to TeV energies. These leptons are responsible for the diffusive synchrotron and IC radiation from the kpc-scale jets. Contrary to the inner jet collision models, leptons accelerated on the shocks do not lose energy close to the shock region (near the stars) but they are injected into the jet. They are transported with the jet plasma to greater distances from the base of the jet, losing energy by the radiation processes mentioned above. Therefore, this high-energy emission is expected to be steady during the timescales of the jet dimension (i.e., thousands of years), in contrast to the emission expected from collisions of stars with the inner jets (below ~1 pc, e.g., Bednarek & Protheroe 1997). Moreover, due to the saturation of the acceleration process of leptons by the synchrotron or advection timescales, the higher energy leptons are expected to be accelerated farther along the jet. Therefore, non-thermal emission from jets should show a clear dependence on the energy, with the lower energy γ-rays produced closer to the base of the jet. We predict that the multi-TeV γ-rays should tend to be produced farther from the base of the jet. In contrast, such a feature may not be observed in the case of synchrotron X-ray emission if the acceleration of leptons is saturated by synchrotron energy losses. Only when the maximum electron energies are constrained by their escape (advection) from the acceleration region should the maximum energies of synchrotron radiation show a dependence of energy on the distance from the base of the jet.

We compared the example spectra obtained in terms of such a model with observations of the intermediate-scale jet in Cen A (Figure 5). It is found that in general the observed level of the X-ray radiation can be explained as a result of the synchrotron radiation produced by electrons accelerated on the shocks around massive stars. On the other hand, the TeV γ-ray emission is expected to be produced by leptons accelerated on the shocks around massive stars (below ~1 TeV) and by electrons accelerated on the shocks around GCs (above ~1 TeV). This hypothesis could be tested in the near future with the operation of the next-generation γ-ray telescopes such as CTA. CTA is expected to reach ~1 arcmin resolution at 10 TeV and an integral sensitivity of ~2 × 10^{-14} TeV cm^{-2} s^{-1} at a few TeV (Acharya et al. 2013). With such angular resolution the TeV γ-ray emission from the kpc-scale jet in Cen A could be resolved and the prediction of energy-dependent emission with the distance from the base of the jet could be confirmed or disproved.

We applied the collision model for radio galaxies whose intermediate jets are expected to be rather slow and observed at a relatively large angle to the line of sight. If the jets still move relativistically on the kpc distance scale, then the non-thermal radiation can be significantly Doppler-boosted (see, e.g., the recent paper by Bosch-Ramon 2015). In such cases the collisions of different types of compact objects (massive stars, red giants, and GCs) with the relativistic jets could provide a natural explanation for the powerful non-thermal emission from blazars observed at a small angle to the line of sight.

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