arXiv:1004.2167v1 [astro-ph.HE] 13 Apr 2010

NON-THERMAL EMISSIONS FROM SHOCKED SHELLS DRIVEN BY POWERFUL AGN JETS

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We explore the emissions by accelerated electrons in shocked shells driven by jets in active galactic nuclei (AGNs). Focusing on powerful sources which host luminous quasars, the synchrotron radiation and inverse Compton (IC) scattering of various photons that are mainly produced in the core are considered as radiation processes. We show that the radiative output is dominated by the IC emission for compact sources ($\lesssim$ 30kpc), whereas the synchrotron radiation is more important for larger sources. It is predicted that, for powerful sources ($L_{\rm j} \sim 10^{47} {\rm ergs\ s^{-1}}$), $\mathrm{GeV-TeV}$ gamma-rays produced via the IC emissions can be detected by the Fermi satellite and modern Cherenkov telescopes such as MAGIC, HESS and VERITAS if the source is compact.

Keywords: Gamma rays; active galactic nuclei; particle acceleration.

1. Introduction

Relativistic jets in radio-loud active galactic nuclei (AGNs) dissipate their kinetic energy via interactions with surrounding interstellar medium (ISM) or intracluster medium (ICM), and inflate a bubble composed of decelerated jet matter, which is often referred to as cocoon. Initially, the cocoon is highly overpressured against the ambient ISM/ICM and a strong shock is driven into the ambient matter. Then a

thin shell is formed around the cocoon by the compressed ambient medium. As in other astrophysical shocks, the shells are expected to be a promising site for particle accelerations, since the shocks are driven into tenuous plasmas. In the present study, we explore the evolution of the non-thermal emissions by the accelerated electrons in the shocked shells. We properly take into account the Comptonization of photons of various origins which were not considered in the previous studies.[1] Focusing on the powerful sources which host luminous quasar in its core, we show, in particular, that the energy of accelerated electrons is efficiently converted through the IC scattering to high energy γ-rays of up to ~ 10 TeV if the source is relatively compact.

2. Model

When considering the dynamics of the expanding cocoon and shell, we neglect the elongation in the jet direction and assume that they are spherical for simplicity. We also assume that the ambient mass density profile has a form of a power-law given by $\rho_a(r) = \rho_0(r/1\mathrm{kpc})^{-1.5}$. We further assume that the kinetic power of jet, L_j, is constant in time. Under these assumptions, the dynamics can be approximately described based on the model of stellar wind bubbles.[2] Then radius of the shock is written as $R(t) \sim 22\rho_{0.1}^{-2/7}L_{45}^{2/7}t_7^{6/7}$ kpc, where $\rho_{0.1} = \rho_0/0.1m_p$ cm^{-3}, $L_{45} = L_\mathrm{j}/10^{45}$ ergs s^{-1} and $t_7 = t/10^7$ yr. Also the total internal energy stored in the shell can be expressed as $E_\mathrm{s} \sim 0.1L_\mathrm{j}t$, implying that roughly 10% of the total energy released by the jet is deposited in the shell.

The energy distribution of the non-thermal electrons is determined by solving the kinetic equation in one-zone approximation which takes in account the injection of electrons and the cooling effects.[3] The electron injection rate $Q(\gamma_e)$ and the cooling rate $\dot{\gamma}_\mathrm{cool}$, which will be described below, are evaluated based on the dynamical model described above.

We assume that the electrons are injected into the post-shock region with a power-law energy distribution given as $Q(\gamma_e) = K\gamma_e^{-2}$ (for $1 \leq \gamma_e \leq \gamma_\mathrm{max}$), where γ_max corresponds to the maximum Lorentz factor. The value of γ_max is obtained by equating the the cooling rate, $\dot{\gamma}_\mathrm{cool}$, to the acceleration rate given by $\dot{\gamma}_\mathrm{accel} = (3/20)(eB\dot{R}^2/\xi m_e c^3)$, where B and $\dot{R}$ are the magnetic field strength in the post-shock region and the expansion velocity of the shell, respectively. Here, ξ is the so-called "gyro-factor" which can be identified with the ratio of the energy in ordered magnetic fields to that in turbulent ones. We postulate $\xi \sim 1$ (Bohm limit), as is observed to be the case for some SNRs. [4–5] Assuming that the magnetic field of ambient ISM/ICM ($\sim$ few μG)[6–7] is adiabatically compressed by the shock, we take $B = 10\mu$G as a fiducial value for the magnetic field strength. The normalisation factor, K, is determined from the assumption that a fraction, ϵ_e, of the energy stored in the shell is carried by the non-thermal electrons. In the present study, as a fiducial case, we assume $\epsilon_e = 0.01$. It is noted that since the factor K is proportionate to ϵ_e and L_j, the resultant luminosity of non-thermal emissions also scales in the same manner with these quantities.

In the cooling rate, $\dot{\gamma}_{\rm cool}$, the adiabatic losses due to expansion of the shell and the radiative losses due to synchrotron and IC emissions are taken into account. Regarding the synchrotron losses, the magnetic field considered above is used. In evaluating the cooling rate for IC scattering, we take into account various seed photons of relevance in this context. The considered photon fields are UV emissions from the accretion disc, IR emissions from the dusty torus, stellar emissions from the host galaxy in NIR, synchrotron emissions from the radio lobe and CMB. We assume that the photons from the disc, torus, host galaxy, and CMB are monochromatic and have the following single frequencies: $\nu_{\rm UV} = 2.4 \times 10^{15}$ Hz, $\nu_{\rm IR} = 1.0 \times 10^{13}$ Hz, $\nu_{\rm NIR} = 1.0 \times 10^{14}$ Hz, and $\nu_{\rm CMB} = 1.6 \times 10^{11}$ Hz. The photons from the radio lobe are assumed to have a continuous spectrum given by $L_{\nu,\rm lobe} \propto \nu^{-0.75}$. In the present study, we focus on powerful sources hosting luminous quasars and adopt $L_{\rm UV} = 10^{46}$ ergs s^{-1} for the luminosity of the UV emissions from the disc. We assume that the luminosity of the IR emissions from the torus is equal to that of the UV emissions ($L_{\rm IR} = L_{\rm UV}$). The luminosity of the host galaxy is assumed as $L_{\rm NIR} = 10^{45}$ ergs s^{-1}. Finally, the luminosity of the lobe is determined by assuming that a fraction η of the jet power is radiated as radio emissions from the lobe (i.e., $L_{\rm lobe} = \eta L_{\rm j}$). Here we assume $\eta = 10^{-2}$ as a fiducial case.

3. Non-thermal Emissions

From the obtained electron distribution, we calculate the spectra of synchrotron and IC radiations. In Fig. 1 we show the photon fluxes, νF_ν, for sources located at distance of $D = 100$ Mpc. The left panels show the case for sources with jet powers of $L_{\rm j} = 10^{45}$ ergs s^{-1}, while the right panels show the case for $L_{\rm j} = 10^{47}$ ergs s^{-1}. The top, middle and bottom panels of the figure correspond to the source sizes of $R = 1$ kpc, 10 kpc and 100 kpc, respectively. In addition to the total photon flux (*thick solid line*), we show the contributions from the synchrotron emissions (*thin solid line*) and the IC scatterings of UV disc photons (*long-short-dashed line*), IR torus photons (*dot-dashed line*), NIR host-galaxy photons (*dotted line*), CMB photons (*long-dashed line*) and lobe photons (*short-dashed line*).

The synchrotron emissions are the main low-frequency component, which extends from radio to $\sim$ keV X-ray. The IC emissions become remarkable at higher frequencies up to ~ 10 TeV gamma-ray. When the source is young and hence small, the radiative output is dominated by the IC emissions, since the energy density of photons is larger than that of magnetic fields (referred to as the IC-dominated stage). As the the source becomes larger, on the other hand, the energy density of photons decreases ($U_{\rm ph} \propto R^{-2}$) and the synchrotron emissions becomes dominant (the synchrotron-dominated stage). Among the contributions to the IC emissions, the scattering of the IR torus photons is the largest at least in the IC-dominated stage thanks to the high energy density of the IR photons. Note that, although the UV disc photons are assumed to have the same energy density as the IR photons, the IC scattering of UV photons is suppressed at the frequencies above $\nu \gtrsim 10^{24}$ Hz

by the Klein-Nishina effect. Then the transition from the IC-dominated stage to the synchrotron-dominated stage occurs roughly at $R_{IC/syn} \sim 27 L_{IR,46}^{1/2} B_{-5}^{-2}$kpc which corresponds to the condition $U_{IR} \sim U_B$. While the contributions from the UV disc photons, host-galaxy photons and lobe photons are modest at best through the entire evolution, the IC scattering of CMB photons dominates over other IC components for sources larger than $R \sim 85 L_{IR,46}^{1/2}$kpc.

The peak luminosities in the spectra are roughly equal to the energy injection rate on the non-thermal electrons ($\gamma_e^2 m_e c^2 Q(\gamma_e) \sim \nu L_\nu$) because the cooling
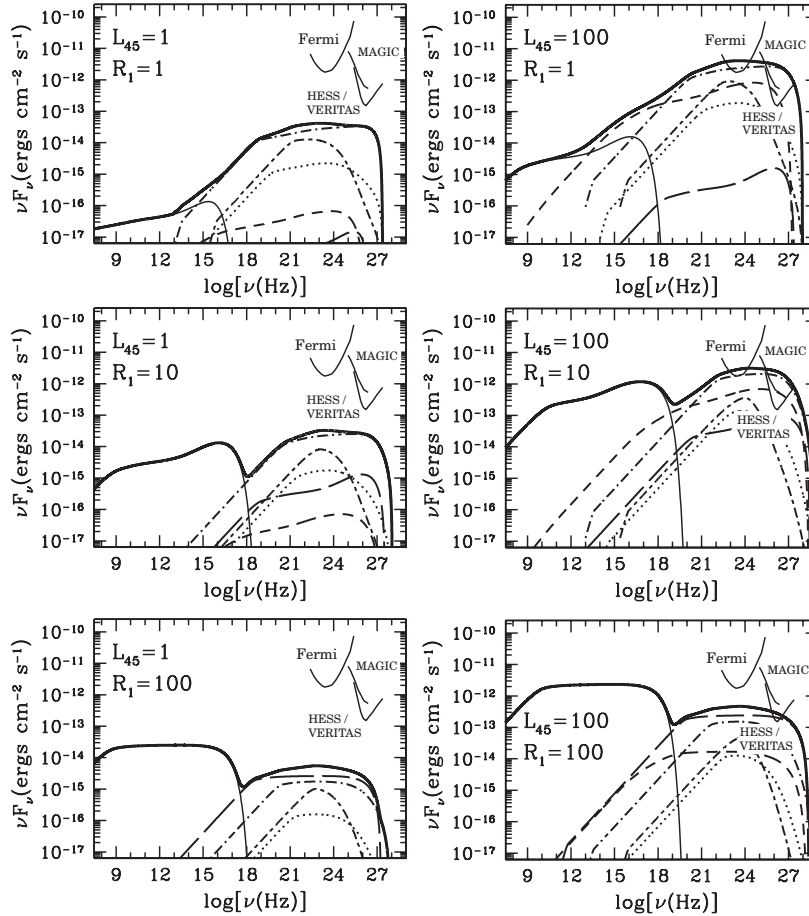

Fig. 1.   The spectra of the synchrotron and IC emissions from sources with the jet powers of $L_j = 10^{45}$ergs s^{-1} (*left panels*) and $L_j = 10^{47}$ergs s^{-1} (*right panels*) located at the distance of $D = 100$ Mpc. The top, middle and bottom panels are displayed for the source sizes of $R = 1$, 10, and 100 kpc, respectively. The various lines show the contributions from the synchrotron emissions (*thin solid line*) and IC scatterings of UV disc photons (*long-short-dashed line*), IR torus photons (*dot-dashed line*), NIR host-galaxy photons (*dotted line*), CMB photons (*long-dashed line*) and lobe photons (*short-dashed line*). The thick solid line is the sum of these fluxes.

time scale of the high energy electrons is shorter than the dynamical time scale (fast cooling). Since the energy injection rate is independent of the electron energy ($\gamma_e^2 Q(\gamma_e) \propto \gamma_e^0$), these non-thermal electrons produce a rather flat and broad spectrum ($\nu L_\nu \propto \nu^0$) in the corresponding frequency range. We can give a rough estimate to the peak luminosity as $\nu L_{\nu,\mathrm{peak}} \sim 5.0 \times 10^{40} \epsilon_{-2} L_{45}$ ergs s^{-1}, or, equivalently, to the peak flux as $\nu F_{\nu,\mathrm{peak}} \sim 4 \times 10^{-14} \epsilon_{-2} L_{45} D_2^{-2}$ ergs cm^{-2}s^{-1}, where $\epsilon_{-2} = \epsilon_e/0.01$ and $D_2 = D/100$ Mpc. The feature is clearly seen in Fig. 1. Indeed, the spectra are flat with a peak flux given approximately by the above estimation. As mentioned in the previous section, the emission luminosity scale approximately linearly with the acceleration efficiency ϵ_e and the jet power L_j. For given values of ϵ_e and L_j, while the value of $\nu L_{\nu,\mathrm{peak}}$ remains nearly constant, the frequency range, where the spectrum is flat, varies with the source size because of the changes in the energy range of the fast cooling electrons and the main emission mechanism (synchrotron or IC). It is emphasized that the peak luminosity is chiefly governed by ϵ_e and L_j and is quite insensitive to the magnetic field strength and seed photons, which will only affect the frequency range of the flat spectrum. This means that if L_j is constrained by other independent methods, [8–9] the observation of the peak luminosity will enable us to obtain information on the acceleration efficiency ϵ_e.

Next we consider the detection prospect. The synchrotron emissions can be observed at frequencies from radio to X-ray. Obviously large sources ($R \gtrsim R_{\mathrm{IC/syn}}$) offer a greater chance of detection than small ones, since the synchrotron radiation is strongly suppressed in the compact sources and the small spatial scale will make it difficult to distinguish the synchrotron radiations from the core emissions of AGN. Even for large sources ($R \gtrsim R_{\mathrm{IC/syn}}$), however, the synchrotron emissions are subject to contaminations with radio emissions from the lobe, optical emissions from the host galaxy and X-ray emissions from ISM/ICM, which are at least partially cospacial. The obtained luminosity of the shell emissions is likely to be lower than that of these emissions. Hence the observation of the synchrotron emissions will be very difficult irrespective of the source size.

In the case of the IC emissions, which are pronounced in gamma-ray, compact sources ($R \lesssim R_{\mathrm{IC/syn}}$) are favored for detection, since the luminosity is higher. Also significant contamination is not expected in this energy range for non-blazar AGNs. At the photon energy of $h\nu \sim$ GeV, the detection limit of the Fermi gamma-ray telescope is roughly $\sim 10^{-12}$ ergs cm^{-2} s^{-1} whereas modern Cherenkov telescopes such as HESS, MAGIC and VERITAS have a detection limit of $\sim 10^{-13}$ ergs cm^{-2} s^{-1} at $h\nu \sim$ TeV. From the estimated peak flux, $\nu F_{\nu,\mathrm{peak}}$, we find that the currently operating gamma-ray telescopes are capable of detecting these emissions at $\sim$ GeV and $\sim$ TeV if the jet power satisfies $L_\mathrm{j} \gtrsim 3 \times 10^{46} \epsilon_{-2}^{-1} D_2^2$ ergs s^{-1} and $L_\mathrm{j} \gtrsim 3 \times 10^{45} \epsilon_{-2}^{-1} D_2^2$ ergs s^{-1}, respectively, and the source size is smaller than $R_{\mathrm{IC/syn}}$. This can be confirmed in Fig. 1 indeed. For the most powerful source with the jet power of $L_\mathrm{j} = 10^{47}$ ergs s^{-1} located at $D = 100$ Mpc, $\sim$ GeV $-$ TeV gamma-rays from the shell may be accessible to the Fermi, MAGIC, HESS and VERITAS gamma-ray telescopes if the source is compact.

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4. Summary

We have explored the temporal evolution of the emissions by accelerated electrons in the shocked shell produced by AGN jets. Below we summarize our main findings in this study.

(i) When the source is young and small ($R \lesssim R_{\rm IC/syn} \sim 27 L_{\rm IR,46}^{1/2} B_{-5}^{-2}{\rm kpc}$), the dominant radiative process is the IC scattering of IR photons emitted from the dust torus. For larger sources, on the other hand, the synchrotron emissions dominate over the IC emissions, since the energy density of photons becomes smaller than that of magnetic fields ($U_B > U_{\rm ph} \propto R^{-2}$). Through the entire evolution, the spectrum is rather broad and flat, and the peak luminosity is approximately given by $\nu L_{\nu,{\rm peak}} \sim 3.0 \times 10^{40} \epsilon_{-2} L_{45}$ ergs s^{-1}, since it is roughly equal to the energy injection rate, which is in turn determined by the jet power $L_{\rm j}$ and acceleration efficiency ϵ_e.

(ii) The spectra of the IC emissions extend up to ~ 10 TeV gamma-ray energies for a wide range of source size ($R \sim 1-100$ kpc) and jet power ($L_{\rm j} \sim 10^{45}-10^{47}$ ergs s^{-1}). For most powerful nearby sources ($L_{\rm j} \sim 10^{47}$ ergs s^{-1}, $D \lesssim 100$ Mpc), GeV $-$ TeV gamma-rays produced via the IC emissions can be detected by Fermi/LAT as well as by the modern Cherenkov telescopes such as MAGIC, HESS and VERITAS if the source is compact ($R \lesssim R_{\rm IC/syn}$). The observation of these emissions enable us to probe the acceleration efficiency ϵ_e of which little has been known so far.

Acknowledgments

References

1. Y. Fujita, K. Kohri, R. Yamazaki and M. Kino, *Astrophys. J.* **663** (2007) L61.
2. J. Castor, R. McCray and R. Weaver, *Astrophys. J.* **200** (1975) L107.
3. K. Manolakou, D. Horns and J. G. Kirk, *Astron. Astroph.* **474** (2007) 689.
4. R. Yamazaki, T. Yoshida, T. Terasawa, A. Bamba and K. Koyama *Astron. Astroph.* **416** (2004) 595.
5. M. D. Stage, G. E. Allen, J. C. Houck and J. E. Davis, *Nature Physics* **2** (2006) 614.
6. D. Moss and A. Shukurov, *Mon. Not. R. Astron. Soc.* **279** (1996) 229.
7. A. A. Schekochihin, S. C. Cowley, R. M. Kulsrud, G. W. Hammett and P. Sharma, *Astrophys. J.* **629** (2005) 139.
8. S. W. Allen, R. J. H. Dunn, A. C. Fabian, G. B. Taylor and C. S. Reynolds, *Mon. Not. R. Astron. Soc.* **372** (2006) 21.
9. H. Ito, M. Kino, N. Kawakatu, N. Isobe and S. Yamada, *Astrophys. J.* **685** (2008) 828.