Inverse Compton emission from relativistic particles accelerated at shear layers in relativistic jets

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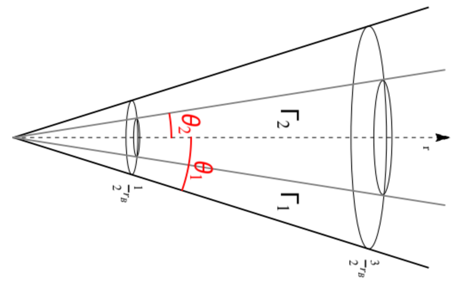
Abstract

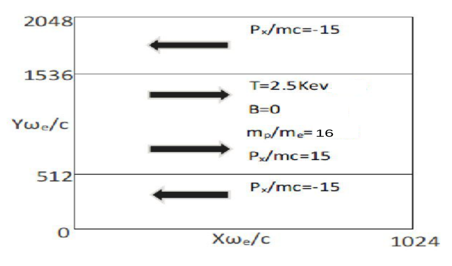
Both observational evidence as well as theoretical considerations from MHD simulations of jets suggest that the relativistic jets of active galactic nuclei (AGN) are radially stratified, with a fast inner spine surrounded by a slower-moving outer sheath. The resulting relativistic shear layers are a prime candidate for the site of relativistic particle acceleration in the jets of AGN and gamma ray bursts (GRBs). We present results of particle-in-cell simulations of magnetic-field generation and particle acceleration in the relativistic shear boundary layers (SBLs) of jets in AGN and GRBs including the self-consistent calculation of the radiation spectrum produced by inverse Compton scattering of relativistic electrons in an external soft photon field.

Spine-sheath Morphology of Relativistic Jets

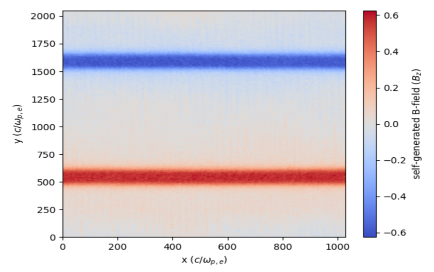
- Relativistic jets are collimated outflows of matter from the accreting black holes residing at the centre of the active galaxies (AGN) that can travel undisrupted over kpc scales.
- Spine-sheath structures of relativistic jets (see fig (a)), with fast-moving inner spine surrounded by the slow-moving sheath have been investigated both observationally and theoretically (Ghisellini et al., 2005). The shear layers formed in the relativistic jets are promising sites for particle acceleration (Alves & et al., 2012; Liang et al., 2013a).
- Particle-in-Cell (PiC) simulations of the pure e^--ion plasma, initially unmagnetized, self-generates magnetic fields due to plasma instabilities (e.g. Weibel instability), which eventually leads to particle energization. For this, we used the TRISTAN-MP code developed by Anatoly Spitkovsky (2005).



(a) Spine-sheath structure of jets



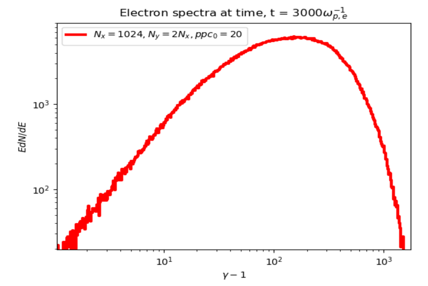
(b) Simulation setup



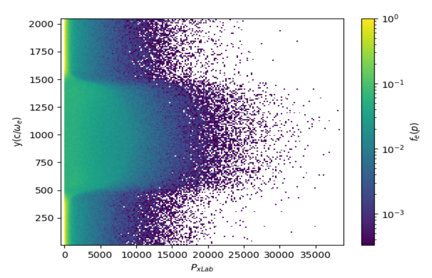
(c) Self-generated B-field at $\omega_p t = 3000$

In the simulation setup (see fig (b)), the spine and sheath propagate with the equal bulk Lorentz factor ($\Gamma = 15$) but in an opposite direction from each other. All simulations are performed in the equal Lorentz factor frame (ELF), which moves with respect to the observer's frame (lab frame) with Lorentz factor Γ . The plasma temperature is 2.5 keV and the ion to electron mass ratio is $m_i/m_e = 16$. The simulation box in $xy - plane$ has grid points 1024 and 2048 along x and y axes. SBLs are formed at $y = 512$ and $y = 1536$. The spatial distances are measured in plasma skin depth while the time is measured in $1/\omega_p$. Value of speed of light is set $c = 0.45\Delta x/\Delta t$ to fulfil the Courant condition. From the simulations, the self-generated magnetic field is developed along $z - axis$ (see fig.(c)).

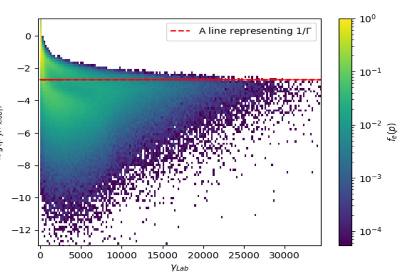
Particle Spectra & Anisotropy



(d) Electron spectra obtained at $\omega t = 3000$



(e) y vs. P_{xLab} plot of electrons



(f) Particle beam angle vs. γ_{lab}

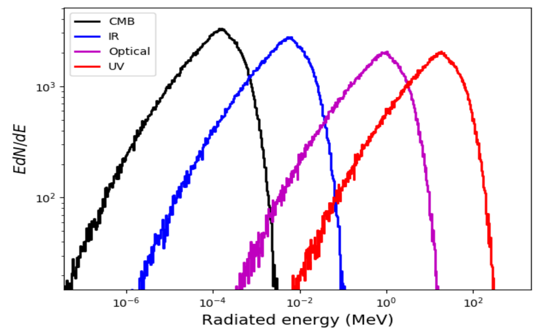
- The electron spectrum peaks around $\gamma_{max} \approx \frac{1}{2}\frac{\gamma_i m_i}{m_e}$. Diffusion of some spine electrons to the sheath region takes place.
- All high energy spine electrons have beam angles much smaller than $1/\Gamma$, where Γ is the bulk Lorentz factor of the plasma. There exists an anticorrelation between beam angle and e^--energy.

Angle-independent Radiation Spectra

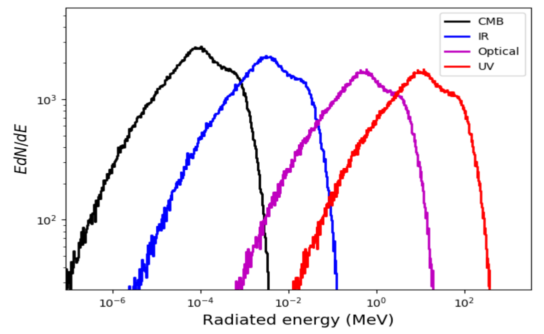
We evaluate electron cooling term assuming a thermal blackbody external radiation field of different temperatures and thus wavelength regimes. Radiation spectra are evaluated using a simple delta-function approximation for the target photon field. The radiation cooling term for inverse Compton scattering of relativistic electrons in the external photon field in the Thomson regime is:

$$\boxed{\left(\frac{d\gamma}{dt}\right)_{rad} = \frac{\pi^4}{15}\sigma_T\, c\, K\, \gamma^2\, \theta^4} \quad , \quad K = \frac{8\pi}{\lambda_c^3}, \quad \theta = \frac{K_B T}{m_e c^2}, \quad \sigma_T \text{ is Thomson cross-section.} \tag{1}$$

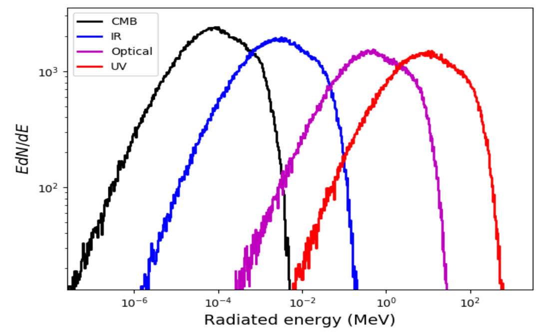
The angle-integrated radiation spectra for different radiation temperatures obtained from the PiC simulations are shown in figures (g), (h) and (i).



(g) Radiation spectra obtained at $\omega_p t = 1500$



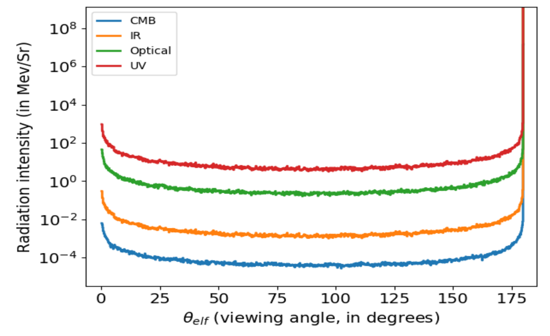
(h) Radiation spectra obtained at $\omega_p t = 2500$



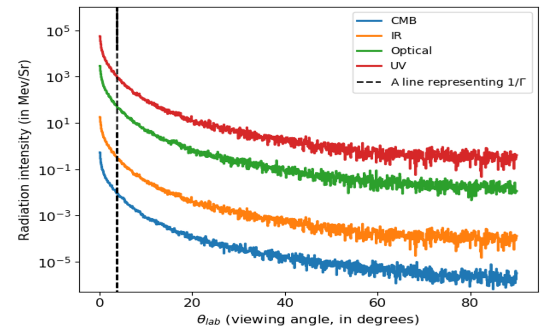
(i) Radiation spectra obtained at $\omega_p t = 3000$

- As the simulations progress, a single component quasi-thermal radiation spectrum develops into a two-component spectrum that eventually becomes a quasi-thermal low-frequency spectrum with a cut-off power-law tail.

For the observation of the radiative output, the frequency-integrated radiation intensity is plotted as a function of the viewing angle (an angle between the direction along which the observer observes the radiation with the jet axis).



(j) Intensity vs. viewing angle in ELF frame at $\omega_p t = 3000$



(k) Intensity vs. viewing angle in the lab frame at $\omega_p t = 3000$

- In the ELF frame, highest radiation intensity is observed along the jet axis ($\theta_{elf} = 0°$ & $\theta = 180°$).
- In the lab. frame, the radiation is strongly beamed in the forward direction, with a characteristic opening angle $\approx 1/\Gamma$.

Angle-dependent Radiation Spectra

In the case of Compton scattering by ultra-relativistic electrons ($\gamma >> 1$), all scattered photons will travel in the direction of the incoming electron (Boettcher & Krawczynski, 2012). Hence the Compton cross section can be approximated as $\frac{d\sigma_C}{d\Omega_s d\epsilon_s} = \delta(\Omega_s - \Omega_e)\frac{d\sigma_C}{d\epsilon_s}$, where Ω_s & Ω_e denote directions of photons and electrons.

$$\frac{d\sigma_C}{d\Omega_s d\epsilon_s} = \frac{\pi r_e^2}{\gamma\epsilon'}\left\{y + \frac{1}{y} - \frac{2\epsilon_s}{\gamma\epsilon' y} + \left(\frac{\epsilon_s}{\gamma\epsilon' y}\right)^2\right\} H\left(\epsilon_s\,;\, \frac{\epsilon'}{2\gamma}\,,\, \frac{2\gamma\epsilon'}{1+2\epsilon'}\right) \quad \textit{(Boettcher \& Krawczynski, 2012)}$$

Here, $y = 1 - \frac{\epsilon_s}{\gamma}$ and $\epsilon' = \gamma\epsilon(1 - \beta\mu)$. The Compton emissivity can be written as:

$$\mathrm{j}(\epsilon, \gamma, \mu) = \frac{3 m_e c^3 \sigma_T \epsilon_s}{8\gamma}\int_0^\infty \frac{1}{\epsilon'}\left\{y + \frac{1}{y} - \frac{2\epsilon_s}{\gamma\epsilon' y} + \left(\frac{\epsilon_s}{\gamma\epsilon' y}\right)^2\right\} n_{ph}(\epsilon, \theta)\; H\left(\epsilon_s\,;\, \frac{\epsilon'}{2\gamma}\,,\, \frac{2\gamma\epsilon'}{1+2\epsilon'}\right) d\epsilon$$

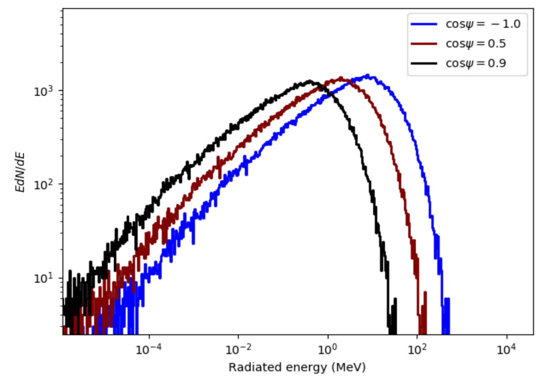
Where, $n_{ph}(\epsilon, \theta)$ is photon density. The blackbody radiation field is strongly peaked near photon energies $\epsilon \cong \theta$. So, a monochromatic δ-function approximation can provide sufficient accuracy for spectral calculation. Hence, $n_{ph}(\epsilon, \theta) = n_{ph}(\theta)\delta(\epsilon - \theta)$ Where, $n_{ph}(\theta) = K\theta^3\Gamma(3)\zeta(3) \;=\; 2.4K\theta^3$.

So, the cooling term for inverse Compton scattering of relativistic electrons in angle-dependent photon field in the Thomson regime is:

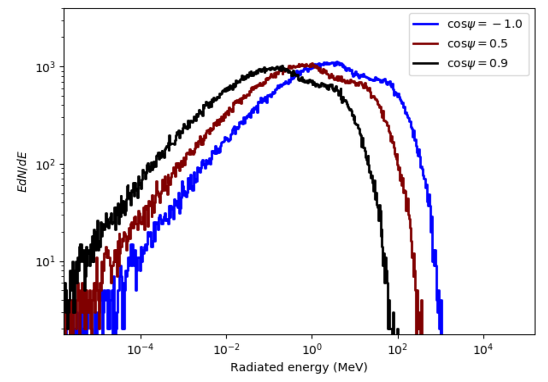
$$\boxed{\begin{aligned}\frac{\mathrm{d}\gamma}{\mathrm{dt}}(\mu, \gamma, \theta) = \frac{2.4 \times 3c\sigma_T K\theta^2}{2.7 \times 8\gamma^2(1-\beta\mu)}\Bigg[&\left(\epsilon_{s_{max}}^2 - \epsilon_{s_{min}}^2\right) + \frac{\epsilon_{s_{max}}^4 - \epsilon_{s_{min}}^4}{4\gamma^2} + \frac{\epsilon_{s_{max}}^5 - \epsilon_{s_{min}}^5}{5\gamma^3} - \\ &\frac{2}{2.7\theta(1-\beta\mu)}\left\{\frac{(\epsilon_{s_{max}}^3 - \epsilon_{s_{min}}^3)}{3\gamma^2} + \frac{\epsilon_{s_{max}}^4 - \epsilon_{s_{min}}^4}{4\gamma^3}\right\} + \frac{1}{\gamma^4}\frac{1}{(2.7\theta)^2(1-\beta\mu)^2}\Bigg\{ \\ &\frac{\epsilon_{s_{max}}^4 - \epsilon_{s_{min}}^4}{4} + \frac{2\left(\epsilon_{s_{max}}^5 - \epsilon_{s_{min}}^5\right)}{5\gamma} + \frac{\epsilon_{s_{max}}^6 - \epsilon_{s_{min}}^6}{2\gamma^2} + \frac{4\left(\epsilon_{s_{max}}^7 - \epsilon_{s_{min}}^7\right)}{7\gamma^3}\Bigg\}\Bigg]\end{aligned}} \tag{2}$$

where $\epsilon_{s_{max}} = \frac{5.4\gamma^2(1-\beta\mu)\theta}{1+5.4\gamma\theta(1-\beta\mu)}$ and $\epsilon_{s_{min}} = \frac{2.7\theta(1-\beta\mu)}{2}$ and $\mu = \cos\psi$. ψ is the angle between directions of propagation of interacting photon and electron.

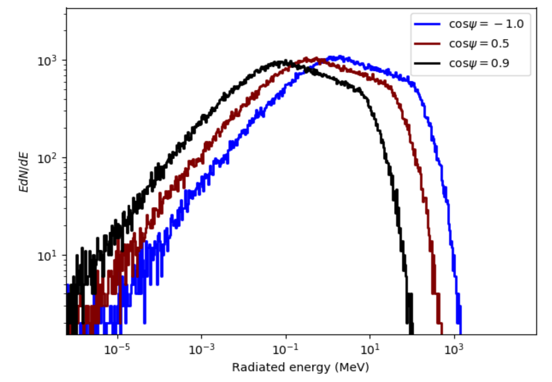
- The radiation spectra due to inverse Compton scattering of relativistic electrons in an angle-dependent UV-photon field are given below.
- The scattered photon energy is maximum for head-on collisions ($\cos\psi = -1$) and decreases for smaller scattering angles, as expected.



(l) Radiation spectra obtained at $\omega_p t = 2000$

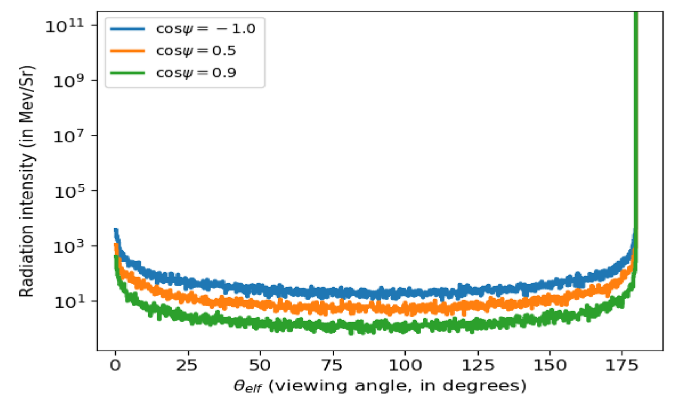


(m) Radiation spectra obtained at $\omega_p t = 4000$

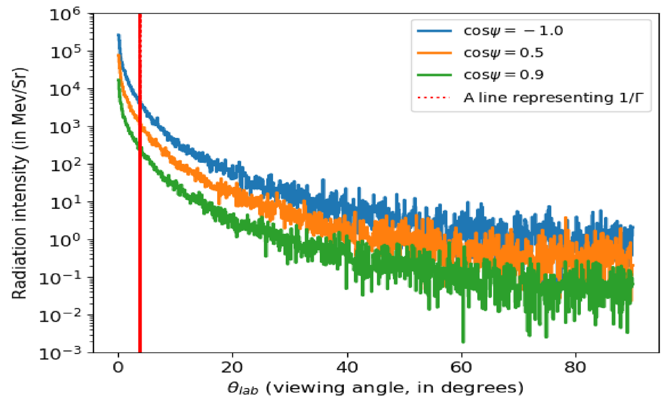


(n) Radiation spectra obtained at $\omega_p t = 5000$

- The angle dependence of the radiation intensity, taking into account angle-dependent electron cooling, is illustrated in Figures (o) and (p) below.
- As in the case of angle-independent electron cooling, the emitted radiation is strongly boosted along the jet axis, with a characteristic opening angle $1/\Gamma$. This boosting, stronger than expected from Doppler boosting of an intrinsically isotropic radiation field in the co-moving frame of the spine, may resolve the long-standing problem of the Doppler factor crisis (Lyutikov & Lister, 2010).



(o) Intensity vs. viewing angle in equal Lorentz factor frame



(p) Intensity vs. viewing angle in the laboratory frame

References

Alves, E.P., Grismayar, T., Martins S.F., et al.: 2012, 746, L14, doi: 10.1088/2041-8205/746/2/l14

Boettcher, M., Harris, D.E., & Krawczynski H.: 2012, Relativistic Jets from Active Galactic Nuclei

Ghisellini, G., Tavecchio, F.: 2005, A&A, 432, 401, doi: 10.1051/0004-6361:20041404

Liang, E., Boettcher, M. & Smith I.: 2013a, The Astrophysical Journal, 766, L19,doi: 10.1088/2041-8205/766/2/l19

Lyutikov, M., & Lister, M.: 2010, The Astrophysical Journal, 722, 197, doi: 10.1088/0004-637x/722/1/197

Spitkovsky, A.,: 2005, AIP Conference Proceedings, 500 doi: 10.1063/1.2141897