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Active Galactic Nuclei Jets and Multiple Shock Acceleration: Depleted Spectra

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Abstract: Shocks in jets and hot spots of Active Galactic Nuclei (AGN) are one prominent class of possible sources of the observed ultra high energy cosmic rays (UHECRs). Extrapolating their spectrum to the plausible injection energy by an assumed shock in the jet, implies an enormous hidden energy for a spectrum of index -2 or steeper. Concerning the AGN jet power, it seems implausible that more than at the very best 1/3 the energy, assuming for example CenA as a main source, goes into the required flux of energetic particles thus, one would need to allow for the possibility that there is a energy problem, which among other aspects, we would like to address in this work. We propose an acceleration model allowing a single injection of particles accelerated consecutively by several oblique (i.e. conical) subluminal and superluminal shocks, along an AGN jet axis. We find that the first shock of a sequence of relativistic conical shocks, establishes a power-law spectrum with $\sim E^{-2.7}$, which favours the local high energy theoretical predictions. The following consecutive shocks push the spectrum up in energy to the UHECRs, rendering flatter distributions, leaving a depletion at low energies, satisfying queries about a puzzling source power. Moreover, our calculations show a variation of spectral slopes, in connection to our inquiry of a single particle injection in multiple shocks and, the properties of relativistic shocks, shedding further light into understanding the jet-shock-magnetic field geometries and consequent produced spectra by AGN jets.

Keywords: cosmic rays, shocks, acceleration, simulations, extragalactic sources, jets

1 Outline

The production and acceleration of ultra high energy cosmic rays (UHECRs) at $\sim E > 10^{18.5}$ eV is believed to arise in plasma shock environments in extragalactic sources. Favorable sources are the hot spots or strong shocks in the jets and radio lobes of Active Galactic Nuclei (AGN) (e.g. [16], [3]) or alternatively, the shocks in Gamma Ray Burst environments (e.g. [21], [20]). In the mechanism of diffusive (1st order Fermi acceleration) shock acceleration (e.g. [2], [7]), particles are repeatedly gain energy in multiple crossings of an astrophysical shock discontinuity due to collisions with upstream and downstream magnetic scattering centers, resulting in a power-law spectrum extending up to the observed UHECRs events. The best simple power-law spectral fit to the UHECR data suggests a spectral index of $E^{-2.4} - E^{-2.7}$ (e.g. [1]). Thus a total power of $10^{48.5} \times D_{10}^2$ erg/s is required, where D_{10} denotes the distance in units of 10 Mpc. Assuming that up to 1/3 of the total jet power can be supplied, then the maximal power possible to be provided in UHECRs is $10^{42.5}$ erg/s for Cen A, and $10^{44.5}$ erg/s for M87 (e.g. [22], [17]), which falls far below than what is required to explain the data. Based on, i) our past studies of cosmic ray relativistic (superluminal and subluminal) shock acceleration properties (e.g. [9], [10], [11]), ii) the re-confinment mechanism in AGN jets [19], iii) the observations of conical shocks in Blazars [8] and iv) by using an analogue to the so-called incomplete Comptonisation [18] - where highly distorted Planck spectra are developing with no creation or destruction of photos in a box filled with hot gas-, we propose here a particle acceleration model in *multiple* relativistic oblique shocks, applied in AGN jets.

2 Numerical method

In this work we have extended the relativistic particle shock acceleration Monte Carlo code by [10], to be applied for *multiple* relativistic oblique shocks. The diffusive acceleration is simulated provided there are shock fronts, where the particles' guiding-center undergoes consecutive scatterings

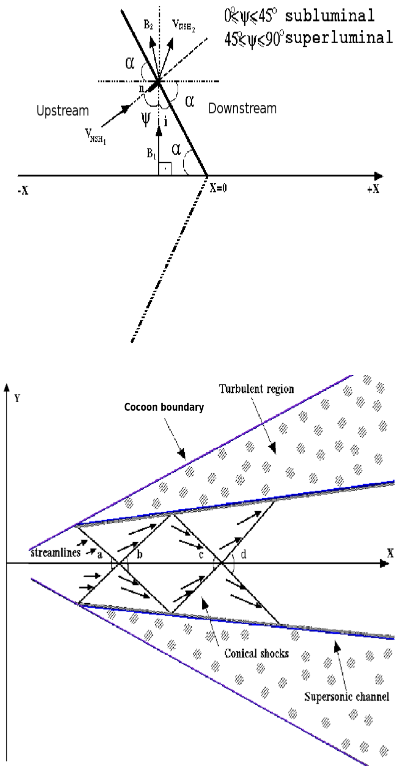

Figure 1: Top: A conical shock as viewed in the normal shock frame, where the vector of the upstream flow velocity is parallel to the shock normal. The magnetic field is oblique to the shock surface by default, so here, in order to facilitate our view clearer on the geometry of two-dimensional conical shock, we show the case of the magnetic field vector (B), perpendicular to the jet axis thus inclined to the shock normal. Here we have chosen for simplicity the magnetic field vector B to be perpendicular to the jet axis. Viewing closely the topology, one sees that, $90^o = i+a$ and $90^o = \psi + i$ then $\psi = a$. Bottom: A two-dimensional topology of repeated conical shocks, with opening angles a, b, c, d, in an AGN jet.

with the assumed magnetized media upstream and downstream each shock. In each shock crossing, particles gain an amount of energy prescribed by the appropriate relativistic jump-condition equations. Furthermore, the basic coordinate system to describe and numerically study a shock is a Cartesian system xyz, where the shock plane lies on the yz plane. In principle, a shock is placed at $x = 0$, while $x < 0$ corresponds to the upstream region and $x > 0$ to the downstream one. The direction of the flow in the shock rest frame is in the positive direction that is, from upstream to downstream. Moreover, allowing a conical two-dimensional shock topology (figure 1, top panel), viewing in the normal shock frame (NSH) and assuming that the flow velocity vector is parallel to the shock normal, one sees that $i + \alpha = 90^o$ and $\psi + i = 90^o$ therefore $\psi = \alpha$, which means that the inclination of the shock surface to the flow, consequently indicates the inclination of the shock to the assumed jet axis (x) in that frame, where α denotes the opening half angle of a conical shock.

Throughout the simulations different frames of reference are used, such as the NSH frame, the fluid rest frames and the de Hoffmann-Teller (HT) frame [5]. In the HT frame one can locally obtain the electric field **E**=0, as in this frame one has the flow everywhere parallel to the magnetic field, with a transformation speed $\beta_{HT} \leq \beta_{NSH} \cdot \tan\psi$, where $\beta = V/c$ and, ψ the inclination of the shock to the magnetic field vector. As long as $\beta_{HT} \leq 1$, then one has a *subluminal* shock. When mathematically β_{HT} is larger than the speed of light, then the *superluminal* shock condition arises, and it is obvious that a HT frame is not allowed. In such a case, the electric field is involved in the particle acceleration process via the so-called 'shock-drift' mechanism.

We start the simulation off the NSH frame and a Lorentz transformation 'brings' the magnetic field vector perpendicular to the jet axis therefore with an inclination to the shock normal (figure 1, top). We assume that the first shock of the sequence of four shocks occurs at about 3000 Schwarzschild-radii from the AGN black hole, see [14], figure 1 (bottom). Injection of a fixed number N_i of particles takes place upstream towards the first shock. The key point here is that in the following three shocks of the sequence, acceleration occurs for the same number of particles without an injection of new particles, as an analogy to incomplete Comptonisation effect, [18]. The energy spectra are calculated in the shock frame downstream and normalized to GeV units, assuming protons as the primary accelerated population. All particles leave the system if they escape far downstream the last shock at $20\lambda(p)$. Alternatively, they leave the system if they reach a specified maximum energy $E_{\max} = 10^{12}$ GeV. Additionally, during the acceleration we choose an escape probability P_e to apply between different shocks ($P_e = 0.1$ for subluminal shocks, $P_e = 0.3$ for superluminal ones), in order to simulate more realistically the compression-decompression between shocks, and shock extension in a repetitive sequence, see [15]. The probability P_e actually gives the fraction of particles of the downstream distribution of each shock that will not be further accelerated. These particles contribute directly to the last shock's downstream distribution. We note that $P_e = 0$, when *all* particles are transported though the subsequent shocks with decompression between them.

The scattering operator in our simulations is treated via a pitch angle scattering approach, see [11]. In the present investigation, we allow particles with pitch angle chosen at random, to lie in the range of $1/\Gamma \leq \delta\theta \leq 10/\Gamma$ (where Γ is the shock's Lorentz factor). Furthermore, we allow $\lambda = 10r_g$ (r_g the particle's gyroradius), which implies a mild turbulence, which is justifiable since there are mostly low magnetized tenuous plasmas in AGN jets further than 3000 Schwarzschild-radii, as we aforementioned.

We note that one has a so-called large angle scattering when particles scatter as $1/\Gamma \ll \delta\theta \leq \pi$, while all the other cases constitute the pitch angle diffusion, with some extreme cases such as $\delta\theta \leq 1/\Gamma$. In this present work we use a fixed pitch angle diffusion with $\delta\theta \leq 10/\Gamma$. For further

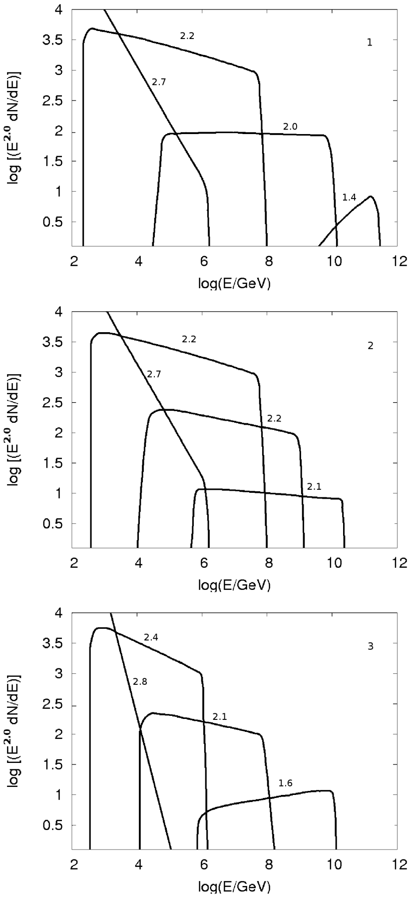

Figure 2: Differential spectra calculated in the shock frame downstream (spectral index value indicated) by sets of four oblique consecutive relativistic shocks. One sees developed flatter spectra (from left to right respectively), depletion in lower energies and extension to higher ones. Panel 1: Spectra by four consecutive subluminal shocks of inclination $\psi = 45^o$ (corresponding to a half opening angle). Panel 2: Spectra from two subluminal shocks and two superluminal shocks ($\psi = 85^o$). Panel 3: Spectra by two superluminal and two subluminal shocks. The spectra have been shifted vertically to allow for better comparison.

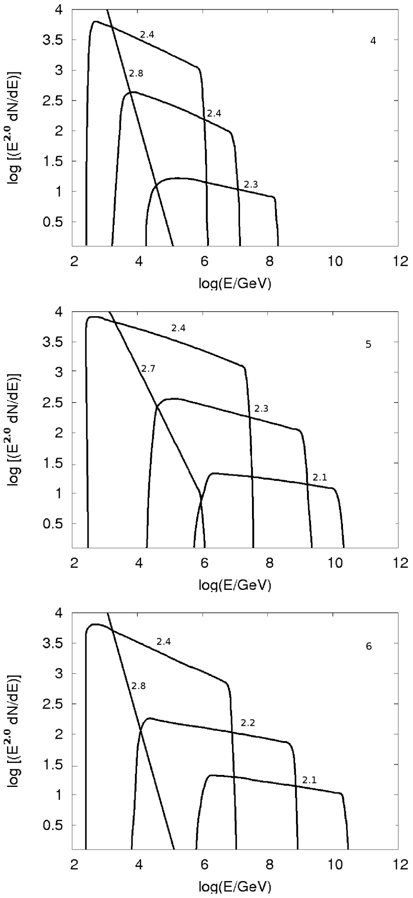

Figure 3: Panel 4: Spectra by four superluminal shocks all four for the same inclination $\psi = 85^o$. Panel 5: Spectra by a sequence of subluminal-superluminal-subluminal-superluminal shocks. Panel 6: Spectra by a sequence of superluminal-subluminal-superluminal-subluminal shocks. The spectra have been shifted vertically for better comparison.

details on the numerical code and kinematics the reader is referred to [11] and [12].

3 Properties of relativistic shocks - Simulations of multiple oblique shocks

In order to facilitate our understanding on the current study, we will first mention some properties of the relativistic shock acceleration (e.g. [9], [10], [11], [12]):

1) Mild relativistic (e.g. $5 \leq \Gamma \leq 50$) quasi-parallel (subluminal) shocks with a pitch angle diffusion (e.g. $\delta\theta \leq \pi/4$ or smaller) produce slightly flatter particle spectra than quasi-perpendicular shocks.

In general, a scatter of pitch angle diffusion generates slightly steeper spectra compared to the the large angle scattering type for all shock inclinations.

2) Highly relativistic (e.g. $50 < \Gamma \leq 900$) quasi-parallel (subluminal) shocks with a pitch angle diffusion of $1/\Gamma \leq \delta\theta \leq 10/\Gamma$, produce slightly flatter particle spectra than their quasi-perpendicular counterparts. Nevertheless, spectral inclinations for highly relativistic shocks render flatter than the mild relativistic or non-relativistic cases.

Finally, 3) highly relativistic quasi-perpendicular (superluminal) shocks with a pitch angle diffusion scatter of $1/\Gamma \leq \delta\theta \leq 10/\Gamma$ generate the steepest spectra compared to all subluminal cases above.

An important finding is that, relativistic subluminal shocks prove to be very efficient accelerators, reaching cosmic ray energies of $\sim 10^{12}$ GeV, while superluminal ones reach only about 10^6GeV.

In this present work we perform simulations allowing diffusive (for subluminal shocks) and shock-drift (for superluminal shocks) acceleration, for *multiple* oblique relativistic shocks. As we aforementioned, we allow an initial injection of particles at the beginning of the acceleration of a fixed number of particles ($N_i = 10^4$ of an initial $\gamma = \Gamma_{sh} + 10$). We use an initial shock Lorentz factor ($\Gamma = 50$) for the first conical pattern (which consists of two oblique shocks with the same apex and inclination angles a and b to the jet axis (x), see figure 1, bottom panel). For the second pair of shocks (inclination angles c and d) we use a $\Gamma = 17$, and this is physically justifiable due to the decompression-compression of the downstream plasma of the precedent conical shock pattern (i.e. velocity compression ratio of 3).

Six different sets of four oblique shocks are used for comparison purposes, and their differential spectra are respectively shown in figures 2, 3. The spectra are recorded in the shock frame downstream each shock at $20\lambda(p)$.

Here we assume protons with no losses, which is justifiable since the magnetic field is weak in AGN jets (i.e. B $=10^{-4}$ Gauss). Moreover, the temperature of an ambient photon field in a jet can be very low, which imposes only a weak loss factor for protons, applying in our case. In that sense the initiation of secondary cascading e.g. $p\gamma$ interaction, is minimal. This is also in accordance with field conditions far off the accretion disk-jet interaction area of the AGN ($>$ 3000 Schwarzschild-radii).

Firstly, by inspecting panel 1 (figure 2), showing spectra by four consecutive subluminal shocks, one sees the maximum particle energy reached compared to other cases, at the impressive $\sim 10^{12}$ GeV. In panel 4 (figure 3), the case of four consecutive superluminal shocks is the least efficient, with a maximum attained particle energy of a modest $\sim 10^8$ GeV. Physically, the latter case would actually require a repetitive set of oblique shocks with very large opening angles ($a, b, c, d \approx 90^o$), meaning continuous decelerating flow, for a distance of around 80 Kpc along the jet, but as discussed in [13] this condition is not realistic. Furthermore, one notices that spectra in each set get gradually flatter. We also observe a distintive gradual decreased flux at lower energies and a consequent 'extension' of the energy distributions to higher energies.

Outlining:

1) The first two shocks in all investigated shock sequences range between spectral index (σ) values of -2.7 to -2.2 for subluminal shocks, and -2.8 to -2.4 for superluminal ones.

2) The sequence of four consecutive subluminal shocks generates the flattest spectra comparing to the rest, with the flattest value σ for the last spectrum at -1.4 along with the highest achieved particle energy at 10^{12} GeV.

3) Four consecutive superluminal shocks generate the steepest spectra with $\sigma \sim -2.3$, and with the lower maximal particle energy of 10^8 GeV.

4) In all six cases, two consecutive subluminal spectra flatten the spectra by 0.5. On the other hand, their superluminal counterparts flatten the spectra by around 0.1. In the first case (panel 1, figure 2) for the four consecutive subluminal shocks, the spectra flatten by 1.3 with a similar behavior for the third case (panel 3, figure 1) of two superluminal and two subluminal shocks, with an overall flattening of 1.2. For the rest of the cases we see an overall flattening by 0.6, 0.5, 0.6 and 0.7 for panels 2, 4, 5 and 6 respectively.

Our acceleration model satisfies queries regarding a puzzling hidden source power fed into the very high energy cosmic rays in AGN jets, and sheds further light into the physics of particle acceleration by relativistic multiple-shock configurations, giving us insights about flat or irregular synchrotron emission spectra from extragalactic sources.

4 Conclusions

We proposed a particle acceleration model in multiple relativistic shocks in AGN jets. Specifically, we performed simulations studying the cosmic ray spectra based on the conical shock formations observed in Lac Blazar jets, e.g. [8], the re-confinement process in AGN jets theorized by [19] and the incomplete Comptonisation effect, see [18].

Our investigation was firstly initiated by the fact that cosmic ray energies with $\geq 10^{18.5}$ eV imply a lot more total source power; but as we proposed here, when flat and depleted cosmic ray spectra are attainable by multiple-shock acceleration, the puzzling extra power to be provided for UHECRs does not seem necessary. By injecting energetic particles once towards a set of oblique (conical) shocks, this would mean that with a smaller number of low energy particles one could have a final particle spectrum extending up to very high energies with depletion at lower energies. We specifically showed, that the first shock form a multiple-shock (conical) sequence, establishes a power-law spectrum with $\sim E^{-2.7}$ in lower energies, which favors the local high energy predictions of [1], and the next consecutive shocks push the particle spectrum up in energy but with flatter energy distributions, leaving a distinctive flux deficiency at low energies, indicated more prominently in the final spectra of each shock sequence. We note that within our model, other particles except protons (e.g. electrons, heavy nuclei), would naturally suffer losses in addition to all the effects from oblique shocks that could accentuate the sharpness of the final spectrum, but at this point we assumed protons in tenuous plasmas, mainly being interested on the very nature of the multiple shock acceleration and the raw spectral distributions at the source.

Our proposed model implies that an $E^{-2.7}$ overall spectrum in the very high energy cosmic ray regime [1] could be explained due to the superposition of several, perhaps many sources, all of which end their acceleration shock sequence with quite flat spectra, as we show here. The present acceleration scenario may also explain the origin of the very high energy cosmic rays by a single AGN source (e.g. Cen A, see [4]), or and flat and irregular gamma-ray and X-ray spectra by various extragalactic sources.

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