UHECRs and multiple shock acceleration in Active Galactic Nuclei Jets

Meli, Athina 1, Biermann, L. Peter 2,3,4,5

1 IFPA, Department of Astrophysics and Geophysics, University of Liege, Belgium 2 MPI für Radioastronomie, Bonn, Germany 3 FZ Karlsruhe, and Department of Physics, University of Karlsruhe, Germany 4 Department of Physics & Astronomy, University of Alabama, Tuscaloosa, AL, US 5 Department of Physics, University of Alabama at Huntsville, AL, USA

E-mail: ameli@ulg.ac.be

Abstract. A prominent source for the production of ultra high energy cosmic rays (UHECRs) is the relativistic shocks in the jets of Active Galactic Nuclei (AGN). As multiple or conical-like shock features have been theorized or observed along the jets of several AGN, we propose here an acceleration model which allows a single injection of particles accelerated consecutively by more than one relativistic shocks (subluminal or/and superluminal) along an AGN jet, by conducting numerical simulations. We find that the first shock of a relativistic shock sequence, establishes a power-law spectrum with \(E^{-2.7}\), while the following consecutive shocks push the spectrum up to the UHECR region of the spectrum, rendering flatter distributions, with characteristic depleted spectra at lower energies. The consequences of this numerical study, shed light into understanding the multiple-shock role in AGN jets, as well as the puzzling source power fed into UHECRs.

1. Introduction

Candidate sources for the acceleration of ultra high energy cosmic rays (UHECRs) at energies \(E > 10^{18}\) eV seem to be the shock formations in the jets 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 spectral fit to the power-law generation spectra of UHECR data suggests a spectral index of \(E^{-2.4} - E^{-2.7}\), e.g. [1]. If this is true, then 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 for example, \(10^{42.5}\) 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 current data. Based on, i) our past numerical studies of relativistic shock acceleration (e.g. [9], [10], [11]), ii) the re-confinement mechanism in AGN jets [19], iii) the observations of conical shocks in Blazars e.g. [8] and iv) by using an analogon, for the particles to be accelerated, 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 (single injection) particle acceleration model in multiple relativistic oblique shocks, to be applied in AGN jets.
2. Numerical method

We have extended the established relativistic particle shock acceleration Monte Carlo code by [10], to multiple relativistic oblique shocks. The diffusive acceleration can be simulated provided there are shock fronts, where the particles’ guiding-centers undergo consecutive scatterings with the assumed magnetized media upstream and downstream each shock. 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. Allowing a conical two-dimensional shock topology (figure 1, left panel), viewing in the normal shock frame (NSH) and assuming that the flow velocity vector is parallel to the shock normal, one sees that $i + \alpha = 90^\circ$ and $\psi + i = 90^\circ$ 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 $\alpha$ 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 $\beta_{HT} \leq \beta_{NSH} \tan \psi$, where $\beta = V/c$ and, $\psi$ the inclination of the shock to the magnetic field vector. As long as $\beta_{HT} \leq 1$, one has a subluminal shock. When mathematically $\beta_{HT}$ is larger than the speed of light, a HT transformation is not allowed and then the superluminal shock condition arises. In this case the electric field is not zero and the so-called ‘shock-drift’ mechanism takes place.

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, right panel). 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 (right). During the acceleration we choose an escape probability $P_{e}$ to apply between the shocks. 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 where they leave the acceleration system in a well defined downstream spatial boundary $r_{b}$, as described in [11]. When $P_{e} = 0$ then all particles are transported though the subsequent shocks. Here, we apply a $P_{e} = 0.1$ for subluminal shocks and $P_{e} = 0.3$ for superluminal ones, in order to simulate more realistically the compression-decompression between shocks in a repetitive sequence, see [15].
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 $\psi = 45^\circ$ (corresponding to a half opening angle). Panel 2: Spectra from two subluminal shocks and two superluminal shocks ($\psi = 85^\circ$). Panel 3: Spectra by two superluminal and two subluminal shocks. Panel 4: Spectra by four superluminal shocks all four for the same inclination $\psi = 85^\circ$. Panel 5: Spectra by a sequence of subluminal-superluminal-superluminal-superluminal shocks. Panel 6: Spectra by a sequence of superluminal-superluminal-superluminal-subluminal shocks. The spectra have been shifted vertically to allow for better comparison.

The scattering operator in our simulations is treated via a pitch angle scattering approach. 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 $\Gamma$ is the shock’s Lorentz factor), which is an appropriate scattering range, implying efficient turbulence due to the relativistic nature of the media, see discussions in [11, 13]. For further details on the numerical code and kinematics the reader is referred to [10].

3. Simulation studies of multiple oblique shocks
Before presenting the current results, it is important to mention that past work of e.g. [9], [10], [11], [12] among other authors, has shown that relativistic subluminal shocks are very efficient accelerators, reaching cosmic ray energies of $\sim 10^{12}$ GeV and flatter power-law distributions.
comparing to non-relativistic counterparts. Superluminal shocks on the other hand, reach lower energies (≤ 10^6 GeV) with steeper primary spectra, given the same conditions as those of the subluminal ones are applied (i.e. scattering media).

In the current work we present a case study, conducting a series of simulations allowing diffusive (for subluminal shocks) and shock-drift (for superluminal shocks) acceleration for more than one shocks. We allow a single injection of particles at the beginning of the acceleration of a fixed number of particles (N_i = 10^4 of an initial γ = Γ_{sh} + 10). Here, we assume protons with negligible losses, due to low background photon fields and weak magnetic field, being well accepted conditions in many AGN jets. As we mentioned above we implement an escape probability of the particles (P_e) to apply between different shocks (i.e. 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 in a repetitive sequence, see [15]. We use an initial shock Lorentz factor (Γ = 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, right panel). For the second pair of shocks (inclination angles c and d) we use a Γ = 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 figure 2. The spectra are recorded in the shock frame downstream each shock.

From the panels of figure 2, one notices that the spectra in each set get gradually flatter. Furthermore and most importantly, we observe a distinctive gradual decreased flux at lower energies and a consequent 'extension' of the energy distributions to higher energies, satisfying queries regarding an AGN puzzling source power, fed into the UHECRs, as we explained in the introduction. This means that with fewer number of particles very high energies can be obtained through multiple shock acceleration. Moreover, the first shock in all sequences develops a spectral index (σ) of about -2.8 to -2.7. The shock sequence of four consecutive superluminal shocks, generate spectra registering a spectral index σ ∼ −2.3 (panel 4), and maximal particle energies of around 10^8 GeV. On the contrary, the sequence of four consecutive subluminal shocks (panel 1) generates flat spectra comparing to the rest, with the flattest value σ for the last spectrum at -1.4, at an impressive attained energy of 10^{11.5} GeV.

4. Conclusions

We proposed a particle acceleration model in multiple relativistic shocks in AGN jets. Specifically, we showed a case study for six different sets of four consecutive oblique shocks, by performing simulations investigating the primary produced cosmic ray spectra, based on the scenario of multiple shock formations observed in AGN, e.g. [8]. To further consolidate our point, we used as analogon to this context, the re-confinement process in AGN jets theorized by [19] and the incomplete Comptonisation effect, see [18].

We specifically showed, that the first shock form a multiple-shock sequence, establishes a power-law spectrum of ∼ E^{-2.7}. Interestingly, the consecutive shocks push the particle spectrum up in energy to the UHECR regime, but with flatter power-law distributions while leaving a characteristic flux deficiency at low energies. Furthermore, as the best spectral fit to the power-law generation spectra of UHECR data suggests a spectral index of E^{-2.4} – E^{-2.7}, e.g. [1], our model favors the later if there was a superposition of several, perhaps many sources, all of which end their acceleration shock sequence with flat spectra shown here. The results of our study could explain the origin of UHECRs in AGN jets, as well as flat or irregular gamma-ray spectra. Very interestingly, as we mentioned in the introduction, the characteristic 'depleted' spectra presented can satisfy queries regarding the AGN puzzling source power fed into the UHECRs.
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