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Neutrinos from active black holes, sources of ultra high energy cosmic rays

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ABSTRACT

A correlation between the highest energy cosmic rays (above ∼60 EeV) and the distribution of active galactic nuclei (AGN) gives rise to a prediction of neutrino production in the same sources. In this paper, we present a detailed AGN model, predicting neutrino production near the foot of the jet, where the photon fields from the disk and synchrotron radiation from the jet itself create high optical depths for proton–photon interactions. The protons escape from later shocks where the emission region is optically thin for proton–photon interactions. Consequently, cosmic rays are predicted to come from FR-I galaxies, independent of the orientation of the source. Neutrinos, on the other hand, are only observable from sources directing their jet towards Earth, i.e. flat spectrum radio sources and in particular BL Lac type objects, due to the strongly boosted neutrino emission.

1. The underlying AGN model

The evidence for a correlation between the arrival directions of ultra high energy cosmic rays (UHECRs) with active galactic nuclei, as reported by the Auger Collaboration [8,9], supports many long standing expectations [46]. The active galactic nuclei with the most detailed available theory to actually accelerate protons to beyond 10^{20} eV are radio galaxies [20]. In all radio galaxies the feeding of outer radio emitting regions is done via a relativistic jet emanating from near a black hole. Shock waves in such jets can accelerate particles just as shocks in the Solar wind do.[1] Shocks in the jet emanating from near the black hole start around a few thousand gravitational radii, as it was shown with detailed spectral fits of the entire electromagnetic spectrum, including the spatial structure at the wavelengths where it is known. The shocks end as strong shocks at kpc or further out [71,72]. It was also shown that when particles get accelerated at the first shock, proton–photon interactions limit their maximal energy [61,68,82].

The correlation with the distribution of active galactic nuclei claimed by the Auger collaboration has been disputed by the HiRes collaboration [1]. However, it is not clear at this point, whether both data sets use the same lower energy cutoff with the same sharpness. This is important, as the MHD simulations of cosmic magnetic fields [31,89] show that scattering of ultra high energy particles rapidly increases with lower energy even near 60 EeV. Thus, with even a slight mismatch between the two data sets the statistics could be very skewed. Using a complete sample of radio galaxy sources and their predicted properties as UHECR sources, these statistics will be explored elsewhere [27,30,35].

1.1. FR-I galaxies and UHECRs

Radio galaxies with extended radio jets were classified into two categories by Fanaroff and Riley [40], a population of high luminosity shows radio lobes at the outer edge of the jet, at kpc scales from the core, *Fanaroff Riley II objects, short FR-II*. The lower luminosity population, on the other hand, has radio knots distributed along the jet, the first knot being as close as ∼3000 Schwarzschild-radii from the central core, *Fanaroff Riley I objects,*

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[1] For a first discussion of the Solar wind, see [18], for shock acceleration in AGN see e.g. [16].

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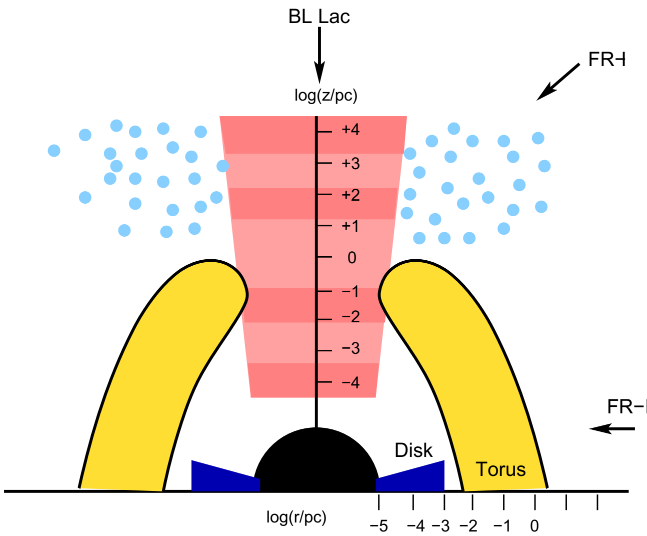

Fig. 1. Schematic figure of the class of FR-I galaxies with double-logarithmic scales. When the jet is pointed directly towards Earth, FR-I galaxies are classified as BL Lac objects. In this model, the torus will hide the accretion disk from view. In the case of a FR-I galaxy without torus, no radiatively efficient disk may be present.

short FR-I. Both radio lobes and knots show non-thermal radio spectra, arising from electron acceleration at a shock front as first theoretically described by Fermi [41,42]. In analogy to processes in the creation of galactic cosmic rays, protons are believed to be accelerated at those shock fronts in the same way as electrons. In particular, oblique shocks can be very efficient in particle acceleration, and use electric fields in shock-drift acceleration due to the Lorentz transformation of the magnetic fields in the proper frame, see [19,53,56,77,78,86,99].

1.1.1. Unified model of FR-I galaxies and BL Lac objects

In this paper, we consider FR-I galaxies as the sources of the UHECRs potentially observed by Auger. It is discussed by others [29,51,57,59,95] that the nearby FR-I galaxy NGC5128, Centaurus A (Cen A in the following), is a good candidate to be responsible for a large fraction of the correlated events above 60 EeV. M 87 is another closeby candidate, see Biermann and Strittmatter [20], which cannot contribute to a possible Auger correlation, since it is barely in Auger's field of view. The large number of more distant FR-I galaxies provide good candidates for the total cosmic ray flux above the ankle. Here, we discuss the morphology of FR-I type galaxies and how these can accelerate particles to the highest energies.

Fig. 1 presents a schematic view of the model of FR-I galaxies that we use in this paper. On the *x*-axis, the rotational-symmetric part of the AGN is shown, while the *y*-axis represents the axis of rotational symmetry along the AGN jet. Both axes have logarithmic units. When the AGN jet is pointed towards Earth, the FR-I type galaxy is viewed as a BL Lac type object [96,97], showing flat radio spectra, with an unresolved jet structure. When the AGN jet is viewed at an angle, the jet structure with radio knots distributed along the jet can be observed. In contrast to the more radio-luminous FR-II galaxies, FR-I type objects typically lack the observation of optical disks. While some of the FR-I type galaxies, such as M 87, clearly lack luminous accretion disks[2] and tori, many objects in this class may have accretion disks hidden behind the torus, provided that the torus is closed around the jet as indicated in Fig. 1, see [38]. In this case, the jet-disk symbiosis model holds also for FR-I galaxies and the disk power scales with the radio luminosity.

1.1.2. Magnetic fields and shock structure in FR-I galaxies

The dependence of the magnetic field in these jets along the jet axis z_j is near $B \sim z_j^{-1}$ at large distances. However, in the inner region, the radial dependence is not certain. Here, we investigate the radial dependence of the magnetic field in order to determine the cosmic rays' maximum energy along the jet and in particular, at the innermost part of the jet.

Observations e.g. [25], suggest that the magnetic field runs as z_j^{-2} at first, since the radio polarization observation show that the magnetic field is parallel to the jet. By analogy to the solutions of div$\mathbf{B} = 0$ in a magnetic wind [86], the magnetic field locally shows a parallel component of $B_{\|} \sim z_j^{-2}$. Further out, the magnetic field observations suggest that, just as in a wind, the magnetic field becomes perpendicular to the flow direction, and so $B \sim z_j^{-1}$. It is obvious that in a smooth wind, any component decreasing with z_j^{-1} will ultimately win over a component running as z_j^{-2}. As the equation of state is almost certainly relativistic e.g. [37,39], the total pressure P depends on the density as $P \sim \rho^{4/3}$, while in a conical simple jet the density $\rho \sim z_j^{-2}$, giving in near equipartition (the magnetic field pressure running with the total pressure) then $B \sim \sqrt{P(r)} \sim z_j^{-4/3}$.

However, repeated shock waves will reheat the material see e.g. Sanders [90], as well as Mach's original work in the 19th century, Mach and Wentzel [65,66]; Mach [64], and so we will assume that the Mach-number of the flow repeatedly comes back to the same value, while the jet flow velocity will stay approximately constant. Therefore, going from crest to crest

$$P \sim \rho, \tag{1}$$

and so as a consequence

$$B \sim z_j^{-1}. \tag{2}$$

This is consistent with the concept that the jet stays approximately conical. This argument is independent of the orientation of the magnetic field, and so the radio polarization observations are not in contradiction, but need then an interpretation as arising from highly oblique shocks, which emphasize magnetic field components parallel to the shock surface. Highly oblique shocks are only possible for high Mach-numbers, which again is consistent.

As one check let us consider a system of repeated conical shocks, and ignore for simplicity the inner Mach disks as shown schematically in Fig. 2 see also Sanders [90]. Then we can see, that given a specific Mach-number at the initial flow formation there will be highly oblique shock waves, which will repeatedly reflect on the conical boundaries, and so produce a self-similar pattern as long as the Mach-number keeps returning to near its initial value. A self-similar repeated structure with an ever increasing inner scale will result. This is precisely what is seen in jet structure at vastly discrepant spatial resolutions, like in the radio galaxy NGC6251 (Bridle and Perley [25], and earlier papers). Further examples for such a shock structure are recent observations of BL Lacertae [73] and the BL Lac type object S5 1803+784 [26].

For those oblique, stationary shocks, it is likely that a mixture of sub- and super-luminal shocks is present.[3] The proton spectra look very different when comparing the two cases. While super-luminal spectra have maximum energies of around 10^5 GeV, subluminal shocks can reach energies up to the highest energies, i.e. $E_{\max} \sim 10^{21}$ eV, as shown by Meli et al. [77].

[2] They are likely to have radiatively inefficient accretion disks, typically for low accretion rates.

[3] The value of the angle between the magnetic field and the shock front normal determines whether a transformation into the Hoffmann–Teller frame ($\mathbf{E} = 0$) is possible (subluminal) or not (super-luminal).