Cosmic Rays from the Nucleus of M87

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Abstract

The unresolved nuclear region of M87 emits strong non-thermal emission from radio to X-rays, and this has been interpreted as jet emission from a mis-aligned BL Lac Object in the context of the Synchrotron Proton Blazar (SPB) model (Protheroe et al 2003). In this model extragalactic cosmic rays are generated as neutrons produced in pion photoproduction interactions decaying into protons after escaping from the host galaxy. Because energetic protons are deflected by the intergalactic magnetic field, the protons from the decay of neutrons emitted in all directions, including along the jet axis where the Doppler factor and hence emitted neutron energies are higher, can contribute to the observed ultra-high energy cosmic rays. We consider the propagation of these cosmic ray protons to Earth and conclude that M87 could account for the observed flux if the extragalactic magnetic field topology were favourable.

1. Introduction

M87 is usually classified as a Fanaroff-Riley Class I (FRI) radio galaxy having a relativistic jet[1] pointing at $\theta \sim 30^\circ$ to the line of sight. The origin of the high-energy component of the SED of M87 may be synchrotron self-Compton [2]. In the context of hadronic models, the spectrum of gamma-ray emission from the nucleus of M87 has recently been predicted (with the subsequent detection of γ-rays by HEGRA telescopes[3]) using the SPB model by Protheroe et al.[4] by treating M87 as a mis-aligned BL Lac object. The SPB model [5] employs hadronic interactions in relativistic jets and the high-energy radiation is produced through photomeson production, proton and muon synchrotron radiation, and subsequent pair-synchrotron cascading in the highly magnetized environment. In the context of the SPB model, M87 could be either an high-frequency peaked (HBL) or a low-frequency peaked (LBL) BL Lac. Protheroe et al.[4] have shown that the M87 jet could contribute also to the pool of extragalactic ultra-high energy cosmic rays (UHECR).

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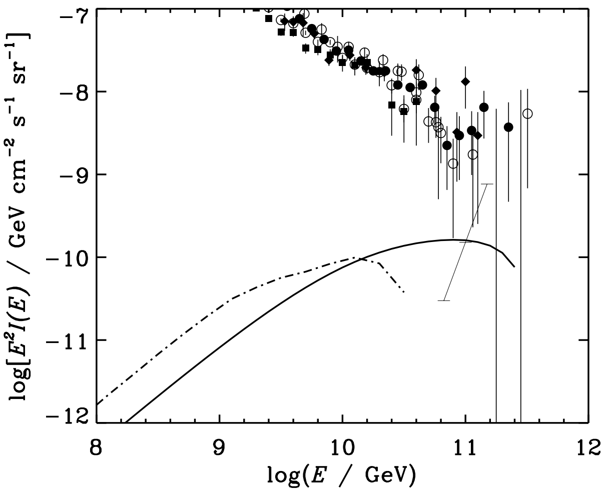

Fig. 1: The observed intensity of UHECR[6]. Chain curve gives the neutron flux that would be observed at Earth from the LBL-type M87 if the neutrons did not decay. The solid curve is the cosmic ray intensity when only straight-line propagation is assumed. The error bar attached to solid curves represents the uncertainty due to the uncertainty in Doppler factor of M87 which we taken to be in the range $0.67 \le \delta \le 1.5$.

2. M87 as a source of UHECR

Energetic protons magnetically trapped in AGN jets lose energy predominantly by Bethe-Heitler pair production and pion photoproduction on ambient radiation fields, or by adiabatic deceleration as the jet expands. Neutron production in pion photoproduction sources ($p\gamma \to n\pi^+$) provides a mechanism for escape of cosmic rays from the jet. Neutrons decay typically after travelling ($E_n/10^{20}$eV) Mpc, which for UHECR is well outside the host galaxy.

The observed intensity of UHECR[6] is plotted in Fig.1. If M87 were an LBL (see [4] for details), then the flux of neutrons divided by 4π sr that would be observed from M87 at Earth if the neutrons did not decay is also plotted in Fig.1. Since these neutrons would travel to Earth in straight lines, and since we take M87 to have a Doppler factor $\delta(\theta \sim 30^\circ) = 1$, the maximum neutron energy that would arrive at Earth would be approximately the maximum jet-frame energy of the accelerated protons, which would be $E_n = 3 \times 10^{19}$ eV for the model shown. However, neutrons decay into protons whose directions are isotropised in the intergalactic magnetic field before and during propagation to Earth. Hence we would have contributions to the protons arriving at Earth from neutrons emitted at all angles with respect to the jet axis. The solid curve in Fig.1 shows the resulting cosmic ray flux divided by 4π sr assuming the Lorentz factor $\gamma_{jet} = 5$ and straight-line propagation.

Diffusion may increase the cosmic ray intensity from M87. For a simple model of intergalactic space with a low magnetic field ($\sim 10^{-9}$ G) and a cell size $L_C \sim 100$ kpc, taking $\lambda(E) \sim L_C$ we calculated an enhancement factor up to $g(E) < 500$, such that the predicted UHECR from M87 could in principle explain the observed intensity above 10^{19} eV.

Next, we included the propagation of protons through the intergalactic magnetic field. A simple wall/void model similar to that used by Medina Tanco[7] is used to illustrate how UHECR would be deflected in complex IGMF structures (see [4] for details). We have found that protons arrive at a sphere of radius 16 Mpc surrounding M87 mostly at positions (latitude, longitude) $(\theta, \phi) = (0°, 0°)$ and $(180°, 0°)$, i.e. close to magnetic field lines threading M87. ($\theta = 0°$ corresponds to the mid-plane of a "wall", and $\theta = 0°$ defines the regular field direction). The cosmic ray flux at 10^9–10^{11} GeV has an enhancement factor at a level $g(\theta, \phi) \approx 10^3$ at $(\theta, \phi) = (0°, 0°)$. The grey-scale in Fig.2 shows the logarithm of $g(\theta, \phi)$. We find that despite of the presence of the turbulent magnetic field component, cross-field diffusion is not strong enough to give rise to significant fluxes far away from the regular field threading the source, at least over a 16 Mpc distance.

3. Conclusion

We predict the UHECR output from M87 to be at a level such that if UHECRs travelled in straight lines they would give an average intensity at Earth a factor ∼20 below that observed. For a constant UHECR output and a simple isotropic diffusion models we find that the predicted intensity could easily account for all the observed UHECR. We note that in perhaps more realistic wall/void models of the IGMF structure, M87 would only be a source of the observed UHECR if the topology of the IGMF between M87 and our Galaxy were favourable. We emphasize that even though the electromagnetic radiation we observe from the M87 jet is not significantly Doppler boosted in energy, the cosmic ray output will be. By this mechanism, the unresolved nuclear core of the M87 jet could emit UHECR with energies up to at least $\sim 3 \times 10^{20}$ eV.

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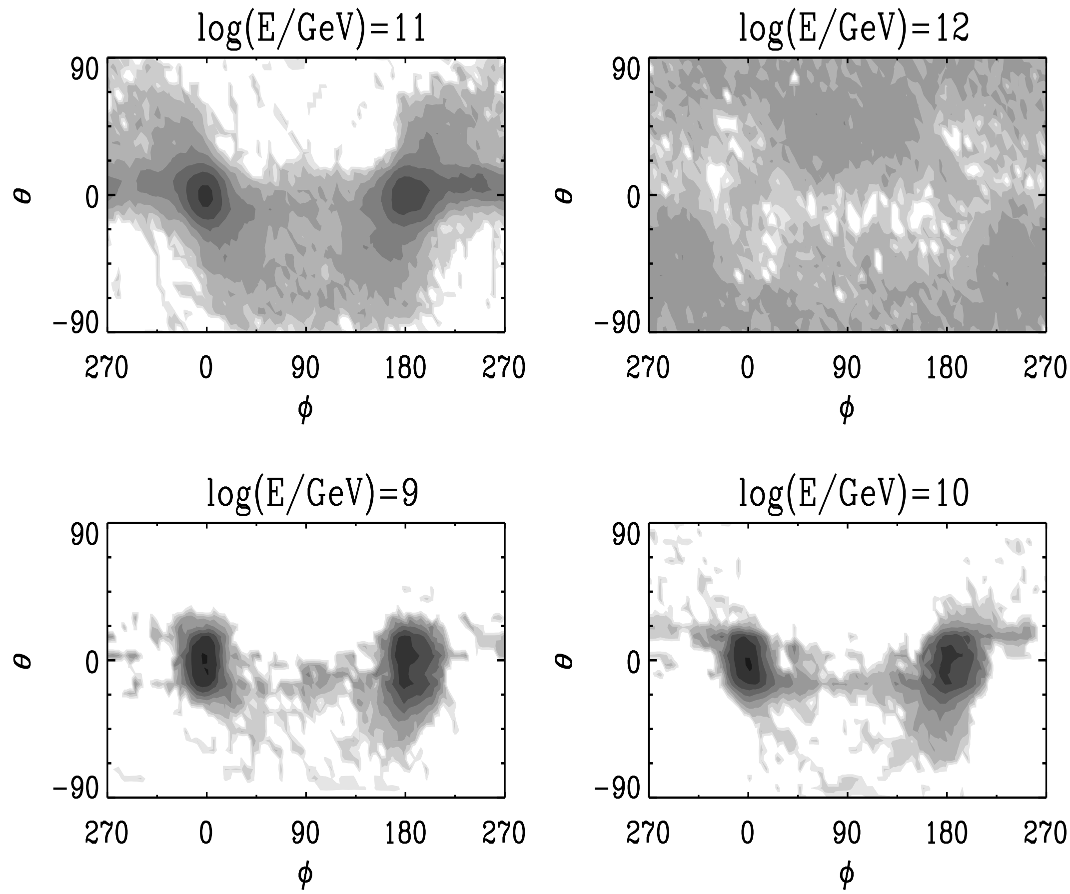

Fig. 2: Enhancement factor $g(E)$ as a function of position (θ, ϕ) on a sphere of radius $\sim$ 16 Mpc centred on the origin for protons of initial energy E as labelled. Gray-scale is logarithmic in $g(E)$ (see text for details). Simulation has been done for 10000 protons isotropically emitted at the origin (defined as the location of M87) and energy losses due to Bethe -Heitler pair production and pion production were included. Positions $(0^\circ, 0^\circ)$ and $(0^\circ, 180^\circ)$ are connected to M87 by a field line of the regular component of the magnetic field, and $\theta = 0^\circ$ corresponds to the mid-plane of a "wall".