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Ultra-high-energy cosmic rays from low-luminosity active galactic nuclei

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ABSTRACT

We investigate the production of ultra-high-energy cosmic ray (UHECR) in relativistic jets from low-luminosity active galactic nuclei (LLAGN). We start by proposing a model for the UHECR contribution from the black holes (BHs) in LLAGN, which present a jet power $P_j \leqslant 10^{46}$ erg s^{-1}. This is in contrast to the opinion that only high-luminosity AGN can accelerate particles to energies $\geqslant 50$ EeV. We rewrite the equations which describe the synchrotron self-absorbed emission of a non-thermal particle distribution to obtain the observed radio flux density from sources with a flat-spectrum core and its relationship to the jet power. We found that the UHECR flux is dependent on the *observed radio flux density, the distance to the AGN, and the BH mass*, where the particle acceleration regions can be sustained by the magnetic energy extraction from the BH at the center of the AGN. We use a complete sample of 29 radio sources with a total flux density at 5 GHz greater than 0.5 Jy to make predictions for the maximum particle energy, luminosity, and flux of the UHECRs from nearby AGN. These predictions are then used in a semi-analytical code developed in Mathematica (SAM code) as inputs for the Monte-Carlo simulations to obtain the distribution of the arrival direction at the Earth and the energy spectrum of the UHECRs, taking into account their deflection in the intergalactic magnetic fields. For comparison, we also use the CRPropa code with the same initial conditions as for the SAM code. Importantly, to calculate the energy spectrum we also include the weighting of the UHECR flux per each UHECR source. Next, we compare the energy spectrum of the UHECRs with that obtained by the Pierre Auger Observatory.

1. Introduction

Cosmic rays (CRs) are a direct sample of matter from outside the solar system, and their study can, for instance, provide important information on the chemical evolution of the universe or improve constraints on Galactic and extragalactic magnetic fields. They can be measured indirectly through the study of extensive air showers that are induced as the CRs hit the top of the atmosphere (known as CR events). The extensive air showers are currently observed using air fluorescence (e.g., High Resolution Fly's Eye (HiRes) experiment[2]) or large array, ground-based detectors (e.g., Akeno Giant Air Shower Array (AGASA)[3]), or both (e.g., Pierre Auger Observatory (Auger)[4]). In the future, space-based detectors might be another option. UHECR particles are mostly protons or fully ionized nuclei with energy above 50 EeV (1 EeV = 10^{18} eV). At such high energies, the flux of UHECRs is very low and only a few dozen particles per square kilometer per century are expected. This is one of the main reasons for the difficulty posed in understanding the origin and nature of the UHECRs. Therefore, very large detector arrays are required. The Pierre Auger Observatory, by far the biggest cosmic ray detection instrument, uses air fluorescence and water detection in a hybrid instrument with an aperture of 7000 km^2 sr.

Joint efforts have been made during the past decade by worldwide, cosmic ray experiments to help us understand from where the UHECRs come and what is their nature. It is believed that the UHECRs originate in extragalactic sources, as the gyroradius of a proton with an energy of 100 EeV is of the order of the dimension

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2 <http://www.cosmic-ray.org>.
3 <http://www-akeno.icrr.u-tokyo.ac.jp/AGASA>.
4 <http://www.auger.org>.

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of our Galaxy, whereas most of the CR particles with energy below 50 EeV originate within our Galaxy (e.g., [15,82,83]). If the UHECR particles are protons, they are subject to energy loss by creating pions through their occasional collisions with the cosmic microwave background (CMB) photons. This process produces a suppression of the cosmic ray energy spectrum beyond 50 EeV, which is known as the Greisen–Zatsepin–Guzmin (GZK) cutoff [49,92]. Therefore, the UHECRs would not be able to survive the propagation from their acceleration sites to us unless their sources are located within ~ 100 Mpc. The presence of the GZK cutoff at the expected energy in the data released by the HiRes collaboration was taken as strong evidence that the UHECR flux is dominated by protons [2].

A suppression of the CR flux has also been observed in the data released by the Pierre Auger collaboration [8,9]. With respect to primary composition, this collaboration has exploited the observation of the longitudinal shower development with fluorescence detectors to measure the depth of the maximum of the shower evolution, $X_{\max}$, which is sensitive to the primary mass. A gradual increase of the average mass of cosmic rays with energy up to 59 EeV is deduced when comparing the absolute values of $X_{\max}$ and RMS($X_{\max}$) to air shower simulations [10].

The data collected by the Pierre Auger Observatory provide evidence for a correlation between the arrival directions of CR events above 55 EeV and the positions of AGN with $z < 0.018$ [6,7,10,11,1], where the region around the position of the radio-galaxy Cen A has the largest excess of arrival directions relative to the isotropic expectations. The correlation is shown for a selection of AGN from the catalog of Véron-Cetty & Véron [87], which do not necessarily follow the same structure as the gamma-ray bursts (GRBs). We emphasize that there is no clear detection of the UHECR sources, just a strong evidence for the anisotropy in the arrival directions of UHECRs.

At highest energies, heavy nuclei may be deflected by Galactic magnetic fields, whereas proton propagation is affected by the CMB, as well as by magnetic deflection, though to a less degree compared to that of particles with higher mass number (e.g., [65]).

UHECRs are most probably accelerated at astrophysical shocks, for instance, through a first-order Fermi mechanism (e.g., [46]), in very powerful systems that can be associated with jets (e.g., [75]) and hot spots in AGN and GRBs [90,88], in large-scale shocks in clusters (e.g., [43]), or as iron nuclei in pulsar winds from rapidly-spinning, young neutron stars [25,42]. Numerical simulations of particle acceleration in shocks have been widely performed using different values for the shock Lorentz factor and background conditions at the shock front (e.g., [14,4,55,54,72,66]); which lead to a slope of the particle distribution of $p \sim [1.5; 2.5]$. Such shocks can also be associated with Poynting flux models for the origin of jets from force-free magnetosphere above accretion disks (e.g., [58,20,26,21,16]). Magnetic reconnection in relativistic jets represents another option for UHECR acceleration (e.g., [47]). As an alternative, Farrar & Gruzinov [44] showed that very intense, short-duration AGN flares that result from the tidal disruption of a star or from a disk instability can accelerate UHECRs. (See also Waxman & Loeb [91]).

In this paper, we propose a model for the UHECR contribution from relativistic jets in LLAGN and calculate the expected energy spectrum of UHECRs using the SAM code developed by Biermann et al. [16], Caramete et al. [31]. For comparison, we also employ the CRPropa code, which is set up with the same initial conditions as the SAM code. The particles in the jet are powered by the BH accretion disk and then accelerated at relativistic shocks with energies up to the ultra-high energy (UHE) domain. We limit the launching area of the jets to the innermost part of the disk located inside the BH ergosphere, where the rotational effects of the space–time are very strong. There are several general relativistic magnetohydrodynamic (GRMHD) codes, the result of which show that the jets can be magnetically driven from a thin disk located inside the BH ergosphere via a Penrose-like process [56,73,67] or via the Blandford–Znajek mechanism (BZ, Blandford & Znajek [24]) when a thick accretion disk is considered [63,64]. (But see the simulations by Fragile et al. [45], where the BZ driven jet does not depend on the disk thickness.) In contrast to the BZ mechanism, where the power of the jet is proportional to the square of the BH spin ($P_{\rm j} \sim a^2$), in the model presented here the dependence of $P_{\rm j}$ on a comes through the launching area of the jets (see the equations in Appendices A and D). In the jets, the electrons lose their energy through synchrotron emission, whereas the protons, as well as heavy nuclei (here, iron nuclei), are capable of surviving the radiative cooling and, perhaps, of propagating through the intergalactic and Galactic medium towards us. Since the particle species undergo the same acceleration process, there must be a correlation between the electron synchrotron emission and the energy of the UHECR particles (protons and iron nuclei). We seek this correlation to make predictions for maximum energy, luminosity, and flux of the UHECRs from nearby LLAGN. This is in contrast to the opinion that only high-luminosity AGN can accelerate particles to UHE domain (e.g., [93]). Taking into account the deflection of the trajectories of the UHECRs in the intergalactic and Galactic magnetic fields, we calculate the distribution of the arrival direction at the Earth and the energy spectrum of the UHECRs. The latter is then compared with the energy spectrum obtained by the Pierre Auger Observatory. We point out that LLAGN as sources of UHECRs were also proposed by Moskalenko et al. [69], where discussions about the implication of AGN jet power and intergalactic, magnetic field configurations for the observed statistical correlation between AGN and UHECR events are presented. Our work is a step further to that of Moskalenko et al. [69], as we include quantitative estimations of UHECR flux using its correlation to the AGN jet power, as well as simulations of UHECR particle propagation in the intergalactic and Galactic magnetic fields. To obtain the energy spectrum of UHECRs, we use a complete sample of 29 LLAGN with a total radio flux density larger than 0.5 Jy [16,31]. About 80% of our sample is contained in the all-sky catalog of local radio galaxies of van Velzen et al. [86], which is used to seek for the correlation between the UHECRs and LLAGN [85]. The fact that some sources of our sample are not included in the catalog by van Velzen et al. [86] might be attributed to the difference in the data; i.e., the frequency at which the radio flux density was measured: 5 GHz in our case and 1.5 GHz and 843 MHz in the case of van Velzen et al. [86].

In Section 2, we provide a description of the model for the UHECR contribution from relativistic jets in LLAGN. We derive the luminosity and flux of the UHECRs based on the relation between the jet power and the observed radio flux density for a flat-spectrum core source (see Appendix C) and calculate the particle maximum energy taking into account the spatial limit and synchrotron emission losses. In Section 3, we provide the predictions for nearby galaxies as possible sources of UHECRs by employing the SAM code. For comparison, we also use the CRPropa code with the same input setup as for the SAM code. We then compare the results of the two codes with those obtained by the Pierre Auger Observatory. In Section 4, we present a summary of the key points and discuss the implication of this model for further studies of UHECRs.

2. Description of the model for UHECR source

2.1. Model conditions

- We assume that the UHECRs are accelerated by shocks in AGN jets, which are launched from the inner accretion disk which is located inside the BH ergosphere, where the rotational effects