ULTRA-HIGH ENERGY COSMIC RAYS LUMINOSITY FROM MULTI-MESSENGER ANALYSIS*

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The ultra-high energy cosmic rays (UHECR) originate probably from extragalactic sources, *e.g.*, Starburst, Radio Galaxies, and Active Galactic Nuclei (AGNs). In the present work, we obtain the upper limits of the cosmic-ray luminosity of Starburst galaxies. The method described in A.D. Supanitsky, V. de Souza, *J. Cosmol. Astropart. Phys.* **2013**, 023 (2013) and R.C. Anjos, A.D. Supanitsky, V. de Souza, *J. Cosmol. Astropart. Phys.* **2014**, 049 (2014) is a productive tool for obtaining the upper limits of the cosmic-rays luminosity and illustrates techniques to study the origin of UHECR from gamma rays at GeV–TeV. The method has been used with the upper limit on the GeV–TeV gamma-ray flux measured by space and ground instruments, such as *Fermi*-LAT, VERITAS, H.E.S.S., and MAGIC. It connects a measured upper limit on the integral flux of GeV–TeV gamma-rays and the UHECR cosmic-ray luminosity of a point source.

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1. Introduction

Cosmic rays are charged particles traveling at nearly the speed of light, following curved paths in the magnetic fields of the universe [1, 2]. The UHECR experiments do not directly access the information on UHECR

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point sources due to the lack of a strong correlation between arrival direction and source position. On the other hand, data from the Pierre Auger Observatory indicated a possible correlation between the arrival directions of the UHECR and the celestial direction of the 23 brightest nearby starburst galaxies (SBGs) [3]. Inside SBGs, the large extent of the superwind region can host high-energy cosmic rays with magnetic fields. The high metallicity of the wind gives an environment of particle acceleration. Superwinds in SBGs were speculated about 20 years ago, making them strong candidates for particle acceleration at very high speeds [4–6].

As they propagate through the universe, accelerated charged particles from SBGs can produce secondary particles (multi-messengers). The integral flux of GeV–TeV gamma rays from cosmic-ray propagation may result in an upper limit on total cosmic-ray luminosity. The calculated upper limit on the GeV–TeV gamma-ray flux is sufficiently constraining to provide an upper limit on the total cosmic-ray luminosity from sources in the UHECR [7, 8].

2. Discussion and results

The method has been applied in several environments [9, 10]. In this work, we obtain the upper limits on the cosmic-ray proton luminosity from gamma rays for the SBGs galaxies NGC 253 and Arp 220 propagation using CRPropa3 [11]. The method considers the contribution of the point source to the total flux measured by the Pierre Auger Observatory.

Since no gamma-ray observations from NGC 253 and Arp 220 were found [12], upper flux limits were derived with the High Energy Stereoscopic System (H.E.S.S.) at the 95% confidence level. The secondary gamma-ray flux is proportional to its cosmic-ray flux or luminosity produced by NGC 253 and Arp 220. Therefore, the gamma-ray production is conservative and a function of cosmic ray luminosity, which can be expressed as follows [8]:

$$L_{\mathrm{CR}}^{\mathrm{UL}} = \frac{4\pi D^2 \left(1+z_{\mathrm{s}}\right)}{\sum_A f_A \frac{K_\gamma^A}{\left\langle E_0^A \right\rangle} \int_{E_{\mathrm{th}}}^{\infty} \mathrm{d}E_\gamma \, P_\gamma^A \left(E_\gamma\right)} I_\gamma^{\mathrm{UL}} \left(> E_\gamma^{\mathrm{th}} \right) . \tag{1}$$

Here, D_{s} is a source at a comoving distance from Earth, A is the nuclei composition, z_{s} is the redshift of the source, $\langle E_0 \rangle$ is the mean energy of the particles in the source, L_{CR} is the total luminosity of cosmic rays, f_A is the fraction of composition A in the total luminosity, $P_\gamma(E)$ is the energy distribution of gamma rays arriving at Earth, and K_γ is the number of gamma rays produced by cosmic-ray particles. In Table 1, we show the values of upper limits for the UHECR proton luminosity for NGC 253 and Arp 220 using Eq. (1).

Table 1. Upper limits for the UHECR proton luminosity for NGC 253 and Arp 220 from gamma-rays observations.

Sources	Distance Mpc	UL: F (> 1 TeV) $[10^{-14}$ ph cm^{-2} s$^{-1}]$	Proton luminosity $[\mathrm{erg\,s^{-1}} \times 10^{42}]$
NGC 253	3.52	0.0471	1.6
Arp 220	77	2.95	68

3. Conclusion

Upper limits for the UHECR proton luminosity for NGC 253 and Arp 220 were calculated using the measured upper limit for the integral GeV–TeV flux and a model for the propagation of UHECR particles from the source to Earth. The luminosity of UHECR is a fundamental constraint on the proposed models, and combining this multi-messenger information will undoubtedly shed light on the puzzle of UHECR generation. The actual acceleration in starburst galaxies will depend on the efficiency of the acceleration process, the age of the accelerator, and the losses of the particles. The results obtained are the effects of UHECR propagation and show the importance of propagation analysis to derive theoretical models for a better understanding of the physics of cosmic rays.

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