A CONNECTION BETWEEN TEV GAMMA-RAY FLUX AND COSMIC RAYS IN THE SEYFERT GALAXY NGC 1068*

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Hadronic interactions in cosmic-ray propagation can produce charged and neutral pions. The neutron pion decays into photons, while positrons and electrons are produced due to the decay of charged pions. The basic mechanisms that can produce gamma-ray fluxes associated with jets of cosmic rays are the decay of neutral pions electron/positron bremsstrahlung, and inverse Compton scattering. These cascade processes show a correlation between the upper limit on the integral GeV–TeV gamma-ray flux and the ultra-high energy cosmic rays (UHECR) luminosity. We calculate the UHECR cosmic-ray luminosity for the NGC 1068 galaxy using the upper limits on TeV gamma-ray flux by H.E.S.S. and MAGIC observatories. We compare our neutrino flux to current estimates of NGC 1068 neutrino flux.

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1. Introduction

In high-energy astrophysics, the mystery of the origin of cosmic rays is a central issue. The individual sources contributing to the total cosmic-ray spectrum are not yet known [1, 2]. The Pierre Auger Collaboration has found evidence for a possible correlation between UHECRs and nearby starburst galaxies [3].

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Starburst-driven (SBGs) galactic winds (superwinds) in starburst galaxies make them strong candidates for accelerating particles at very high velocities. Superwinds are the result of hydrodynamic interaction between the primary energetic wind fluid and the surrounding interstellar medium [4–7].

Possible sources contributing significantly to the extragalactic gamma-ray and neutrino background include starburst galaxies and star-forming active galactic nuclei. NGC 1068 is the brightest of the star-forming galaxies and produces gamma rays with energies ranging from 0.1 to 50 GeV. The MAGIC Collaboration recently reported on a search for gamma-ray emission in the extremely high-energy range. No significant signal was detected during the 125-hour observation of NGC 1068. The null result establishes a 95% C.L. upper limit on gamma-ray flux above 200 GeV of $5.1 \times 10^{-13}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ [8]. In addition, IceCube has detected an excess of neutrino events over the isotropic background from the direction of NGC 1068. Although this excess is not statistically significant at present, it is interesting to consider the possibility that it correlates with a real signal [8, 9].

Accelerated charged particles from SBGs can produce messenger particles (gamma rays and neutrinos) as they travel through the cosmos. The total cosmic-ray luminosity may be limited by the integral flux of GeV–TeV gamma rays from cosmic rays. The predicted upper limit on the GeV–TeV gamma-ray flux is sufficient to set an upper limit on the total cosmic-ray luminosity from UHECR sources [10, 11].

The method we use in this work is based on [10, 11]. If we consider a source at a certain distance from the Earth, it is possible to determine a flux of cosmic rays emanating from this source. This flux already provides the cosmic-ray luminosity, however, the cosmic ray is scattered during its trajectory and loses the direction of the cosmic-ray source. The cosmic-ray flux for a single source is given by

$$I^{\mathrm{UHECR}} = \frac{L_{\mathrm{CR}} W_s(\hat{n})}{4\pi (D_s^2)(1+z)\langle E\rangle_0} K_{\mathrm{CR}} P_{\mathrm{CR}}(E)\,, \tag{1}$$

where I^{UHECR} is the cosmic-ray flux, L_{CR} is the cosmic-ray luminosity for a single cosmic-ray source, W_s is the observatory exposure, z and D_s are the redshift and distance, respectively, for the single source, and $P_{\mathrm{CR}}(E)$ and K_{CR} are the energy distribution and the number of particles reaching Earth.

In this method, all kinds of energy losses during the propagation of the particles of the cosmic radiation are considered, such as electron–positron pair production, photodeintegration and, especially, pion photoproduction. This results in a secondary gamma-ray and neutrino flux given by the following equations:

$$I_\gamma(E_\gamma) = \frac{L_{\rm CR}}{4\pi(D_s^2)(1+z)\langle E\rangle_0} K_\gamma P_\gamma(E_\gamma)\,, \tag{2}$$

where $P_\gamma(E_\gamma)$ and K_γ are the energy distribution and the number of particles of gamma rays produced by the energy-loss processes of the cosmic-ray particles, respectively, and neutrino flux

$$I_\nu(E_\nu) = \frac{L_{\rm CR}}{4\pi(D_s^2)(1+z)\langle E\rangle_0} K_\nu P_\nu(E_\nu)\,, \tag{3}$$

where $P_\nu(E_\nu)$ and K_ν also give the energy distribution and the number of particles, respectively, considering the idea already described for gamma rays.

We assume that all gamma rays and neutrinos produced during propagation are a product of cosmic rays, and that no gamma rays or neutrinos were produced at the source. That is, we assume that all messenger particles (gamma rays and neutrinos) are products of cosmic rays created by the energy losses during propagation described earlier. We use the flux of gamma rays to determine the upper limit of the luminosity of cosmic rays, which is given by

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

where D is a source at a comoving distance from Earth, A is the nuclear composition, $z_{\rm s}$ is the redshift of the source, $\langle E_0\rangle$ is the mean energy of particles in the source, $L_{\rm CR}^{\rm UL}$ is the total luminosity of cosmic ray, 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. Using the results for the upper limit of cosmic-ray luminosity from Eq. (4), we obtain the neutrino flux for the source

$$I_\nu^{\rm UL}\left(> E_\nu^{\rm th}\right) = \frac{L_{\rm CR}^{\rm UL} \sum_A f_A \frac{K_\nu^A}{\langle E_0^A\rangle} \int_{E_{\rm th}}^{\infty} {\rm d}E_\nu P_\nu^A(E_\nu)}{4\pi D^2(1+z_{\rm s})}\,. \tag{5}$$

Therefore, we obtain the maximum luminosity of cosmic rays for the source NGC 1068, and with this result, we obtain values for the upper limit of the integral flux of neutrino flux given by Eq. (5).

2. Discussion and results

The approach has been used in a variety of environments, including [12–14], where the same described here method has been used to obtain the maximum luminosity for other individual sources in different scenarios of composition, particle injection spectrum, and threshold energies.

Using CRPropa3 [15], we have performed simulations that examine the injection spectrum and propagate the cosmic-ray particles from the distance of the individual source and the secondary gamma-ray and neutrino flux generated by the energy loss processes. In this way, we obtain upper limits on the cosmic-proton luminosity from gamma rays and the upper limit on the integral flux of GeV–TeV neutrinos for the propagation of the SBG galaxy NGC 1068. The approach takes into account the contribution of the point source to the total flux observed by the Pierre Auger Observatory. The values for the upper limit of the integral flux of GeV–TeV gamma rays using this method have been described in [12]. However, in this case, we reconstruct the neutrino flux for NGC 1068 using the method already described. We did this for different spectral indices in the simulations, taking into account the distance from the source and the proton composition, to determine the upper limit of the luminosity.

Direct measurements of gamma-ray flux by MAGIC observations were not possible, so upper limits for gamma-ray flux were determined using MAGIC with a 95% confidence level in [12]. Similarly, the secondary neutrino is proportional to its cosmic-ray flux or luminosity produced by NGC 1068. Therefore, the neutrino production is conservative and a function of cosmic-ray luminosity. In Table 1, we show the values of the upper limits on the UHECR proton luminosity and the integral flux of GeV–TeV neutrinos for NGC 1068 using the method described in [10, 11]. We vary the spectral index (alpha) of the source in the simulations to obtain the upper limit of the luminosity for NGC 1068, and we also obtain the upper limits of the neutrino flux obtained using this method.

Table 1. Upper limits for UHECR proton luminosity for NGC 1068 from gamma-rays observations.

α	$L_{\mathrm{CR}}^{\mathrm{UL}}$ (Proton) [erg s^{-1} $\times$ 10^{42}]	I_{ν}^{UL} [10^{-14} cm^{-2} s^{-1}]
2.7	2.78	4.84
2.8	4.46	7.76
2.9	7.21	12.53
3.0	11.0	19.22

Since the upper limit of the integral of the gamma-ray flux obtained from the simulations under the same conditions for a proton composition was higher than the upper limit of the source determined by the MAGIC observatory, we can determine the upper limits of the UHECR proton luminosity for NGC 1068 and the neutrino flux in different scenarios (by varying the spectral index).

3. Conclusion

The luminosity of the UHECR is a fundamental constraint on the proposed models. Several constraints can be imposed on a model designed to describe the origin of UHECR. We determine the upper limit of the UHECR proton luminosity for NGC 1068 and use this result to provide predictions for the neutrino fluxes for the same source. A neutrino signal detected from NGC 1068 would provide compelling evidence for the presence of a hadronic component in the gamma-ray spectrum. In the next few years, until the Cherenkov Telescope Array (CTA) [16] is fully completed around 2025, the era of multi-messengers will be the new great scientific success in astrophysics that will allow us to decipher the many emission processes.

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