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Upper limits on the cosmic-ray luminosity of supernovae in nearby galaxies

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Interactions between cosmic rays and also between cosmic rays and particles of the Cosmic Microwave Background and the Extragalactic Background Light produce charged and neutral pions. The mechanisms that can produce gamma-ray fluxes associated with cosmic rays are the decay of neutral pions, bremsstrahlung, and inverse Compton scattering from pions. These cascading processes show a correlation between the upper limit on the integral GeV-TeV gamma-ray flux and the upper limit on the UHECR luminosity, motivating the study of the multi-messengers to calculate luminosities of UHECRs for specific point sources. We examine the possible sites of ultra-high energy cosmic-ray acceleration in supernovae in nearby galaxies, which were measured by the High Energy Stereoscopic System (H.E.S.S.). The upper limits on the UHECR cosmic-ray luminosity of these sources are calculated with a particular focus on the sources that produce a mixed composition.

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1. Introduction

Cosmic rays (CRs) can be accelerated to high energies and travel at almost the speed of light. We know little about their origin, in particular where they come from and how they are accelerated [1, 2]. Interactions between CRs themselves and also between CRs and particles of the cosmic environment (hadronic interactions) produce charged and neutral pions. The neutron pion decays into two photons, while positrons and electrons are produced due to the decay of charged pions. The three basic mechanisms that can produce gamma-ray fluxes associated with CRs are: i) the decay of neutral pions, ii) electron/positron bremsstrahlung, and iii) inverse Compton scattering of light by electrons/positrons coming from pions. These cascade processes show a correlation between the upper limit on the integral GeV - TeV gamma-ray flux and the upper limit on the ultra-high energy CRs (UHECRs) luminosity [3, 4], motivating multi-messenger studies to calculate the luminosities of UHECRs for specific point sources.

The interaction between cosmic rays and the extra-galactic photon background generating multi-messenger particles is an important aspect to be studied to get information from the sources. The source BL Lac object TXS 0506+056was found to be active in high-energy gamma-rays and very-high-energy gamma-rays with Fermi-LAT and MAGIC telescopes, respectively [5]. Together with observations in gamma-rays, TXS 0506+056is the first observed astrophysical source associated with high-energy neutrinos, detected by the IceCube Observatory – IceCube-170922A [6]. Thus, the production of CRs, gamma-rays, and neutrinos are always interconnected and the complete understanding of the sources and acceleration mechanisms will be possible with a multi-messenger analysis.

2. Observations and results

The method was explained in detail in [3, 4]. For both works, the measured upper limit (UL) on the integral flux of GeV–TeV gamma-ray was used to constrain the proton and the total (iron) UHECR luminosity. In this paper the SN 2005dn hosted in NGC 6861 is analyzed. Upper limits on the proton and mixed luminosity are set. Studies with additional SNe sources from table 1 is now underway in the presence of extragalactic magnetic fields. We calculate the upper limits on the cosmic-ray luminosity with mixed compositions that fit both measurements on the UHECR energy spectrum and mass composition acquired by Auger Collaboration [7].

Since no gamma-ray measurements were observed from SNe (table 1), flux upper limits (ULs) have been derived by High Energy Stereoscopic System (H.E.S.S.) at the 95% confidence level with index $\Gamma = 2$ [8], and it is possible to associate the integral flux of GeV–TeV gamma-ray measured with UHECR luminosity. We assume an isotropic cosmic-ray emission. The secondary gamma-ray flux is proportional to its cosmic-ray flux or luminosity produced by NGC 6861. Therefore, the production of the gamma-rays is conservative and in function of the cosmic-ray luminosity that may be expressed [4]:

$$L_{CR}^{UL} = \frac{4\pi D^2(1+z_s)}{\sum_A f_A \frac{K_\gamma^A}{\langle E_0^A \rangle} \int_{E_{th}}^{\infty} dE_\gamma P_\gamma^A(E_\gamma)} I_\gamma^{UL}(> E_\gamma^{th}) \tag{1}$$

where D_s is a source at 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 particles in the source, L_{CR} is the total cosmic-ray luminosity, f_A is the fraction of the total luminosity for composition A, $P_\gamma(E)$ is the energy distribution of gamma-rays arriving on Earth and K_γ is the number of gamma-rays generated from cosmic-ray particle. The calculus taking into account the weight of the point source to the total measured flux by Pierre Auger Observatory.

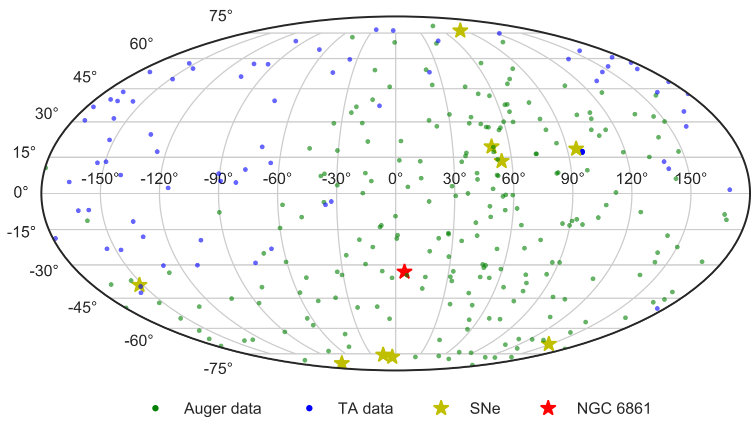

Figure 1: UHECR event locations with SNe in Galactic coordinates. The green points indicate the arrival directions of 231 events with $E > 52$ EeV and zenith angle $\theta < 80$ from Pierre Auger Observatory [9]. The blue points indicate the arrival directions of 72 events with $E > 57$ EeV and $\theta < 55$ from Telescope Array [10]. The stars indicate the location of nearby galaxies from table 1.

Table 1: Supernovae parameters observed with H.E.S.S.. The upper limits are computed assuming 95% confidence level and a power-law index of 2 [8]

Host galaxy	SNe	Dist. (Mpc)	Flux UL ($>$ 1TeV) [10^{-13} cm^{2}s^{-1}]
NGC 7755	SN 2004cx	26 ± 5.	1.9
NGC 6861	SN 2005dn	38.4 ± 2.7	0.41
NGC 7793	SN 2008bk	4.0 ± 0.4	4.8.
NGC 3095	SN 2008bp	29 ± 6.	5.5.
NGC 922	SN 2008ho	41.5 ± 2.9	7.7
NGC 175	SN 2009hf	53.9 ± 3.8	5.3
NGC 918	SN 2009js	16 ± 3	11
NGC 4945	SN 2011ja	5.28 ± 0.38	5.2
NGC 4419	SN 2012cc	16.5 ± 1.1	10.
NGC 5128	SN 2016adj	3.8 ± 0.1	1.7

The figure 1 shows the sample of supernovae in nearby galaxies and the UHECRs Auger [9] and TA [10] events around the sources. Some SNe are close to the 'hotspots' measured by the Auger and TA [11] and, therefore, the point source UHECRs luminosity of these sources, calculated from the method described, can contribute to the total luminosity of the 'hotspots'. Figure 2 illustrates the sources for which we can calculate the UHECR luminosity from integral flux of GeV–TeV gamma-ray measurement. If the line (proton or iron) is above the measured upper limit of integral flux of gamma-rays then we can obtain an upper limit on the composition luminosity [3, 4]. Finally, the figure 3 presents the show the upper limit on the cosmic-ray luminosity as a function of the spectral index for NGC 6861 hosting SN 2005dn for several compositions at source and for $E_{cut} = 10^{21}$ eV.

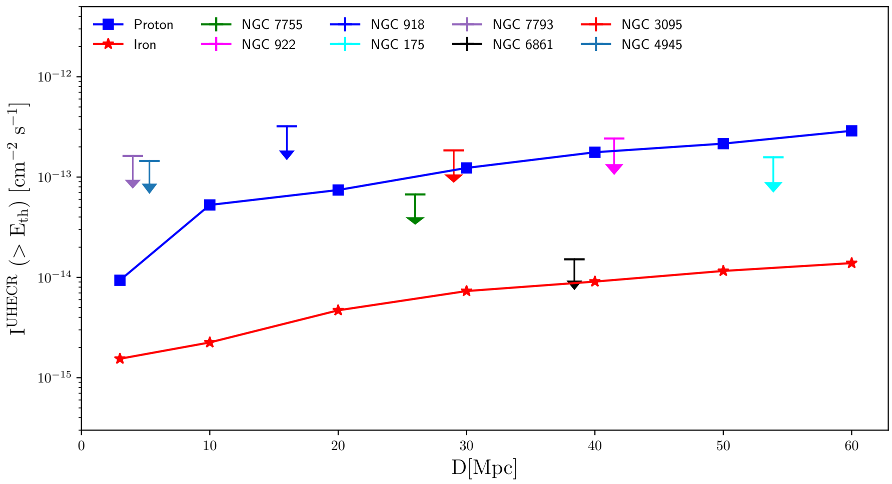

Figure 2: I^{UHECR} as a function of the source distance, calculated by using the upper limit on the flux observed by the Pierre Auger Observatory at 95% CL.

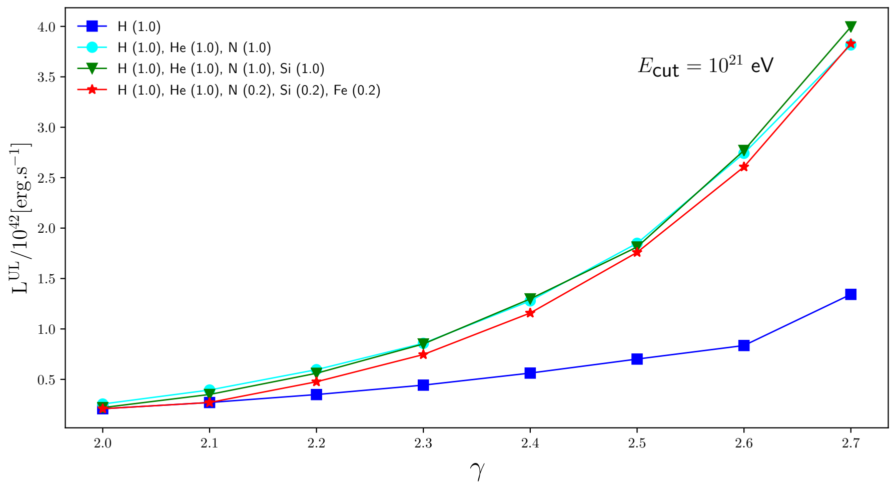

Figure 3: Upper limits on the mixed composition (H; H and He; H, He, N and Si; H, He, N, Si and Fe) cosmic-ray luminosity from gamma-rays observations of the source NGC 6861 as a function of the spectral index and for $E_{cut} = 10^{21}$ eV.

3. Conclusion

Observations of gamma rays establish significant constraints on theories of UHECRs point sources. The upper limits on the UHECR mixed composition luminosity were obtained for the NGC 6861 hosting SN 2005dn. The model shows a direct correlation between the measured upper limit on the GeV–TeV integral flux and the secondary gamma-rays from UHECRs propagation using CRPropa3 [12]. The upper limits on the UHECR luminosity for sources of figure 2 will be investigated in different environments in future papers.

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