PROCEEDINGS OF SCIENCE

Neutrino emission from NGC1068: looking at the contribution of the kiloparsec jet.

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The IceCube telescope recently found an excess of 79 track-like neutrino events at TeV energies correlated with NCG1068 position (equivalent to a significance of 4.2 sigmas). Considering that NGC1068 presents a core with a high star-formation rate and hosts an active galactic nucleus, these observations can be the result of different emitting regions. A recent work based on Atacama Large Millimeter Array (ALMA) data describes the characteristics of the kiloparsec jet associated to this AGN identifying 4 major blobs on its head. In this proceeding we describe the possible non-thermal emission associated with this jet and the bright blobs obtaining their physical parameters from the ALMA observations as well as from the electromagnetic spectral energy distribution (SED). Moreover a lepto-hadronic and a hadronic scenarios have been explored: for the former we associate the electromagnetic SED with the leptonic emission from the blobs, using the synchrotron radiation as the target for the cosmic rays accelerated in the jet or in the observed blobs; for the latter we consider the gas environment around the head of the jet as the molecular target for the accelerated cosmic rays (CRs). We compute neutrino emission implied by these two scenarios and compared it with the IceCube observations for this Seyfert galaxy. We show that a multi-component description of non-thermal emission can't exclude the observed kiloparsec jet from the main emitting regions.

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1. Introduction

The IceCube collaboration recently reported a TeV neutrino point-like excess, at 4.21σ, correlated with the position of the Seyfert II galaxy [15] NGC1068 [1]. The best fit value for the spectral index resulted to be $\gamma = 3.2^{+0.2}_{-0.2}$ while the one obtained for the averaged neutrino flux at an energy of 1 TeV is $\Phi^{1TeV}_{\nu_\mu+\bar{\nu}_\mu} = (5.0 \pm 1.5_{stat} \pm 0.6_{sys}) \times 10^{-11}\mathrm{TeVcm^{-2}s^{-1}}$ [1]. The flux of measured high-energy neutrinos from NGC1068 is more than an order of magnitude higher than the upper limit of TeV gamma-ray emissions from this source. In fact the neutrino luminosity from 1.5 TeV to 15 TeV corresponds to $L_\nu = 2.9 \times 10^{42}$ erg s^{-1} in comparison with the gamma-ray luminosity, $L_\gamma = 1.6 \times 10^{41}$erg s^{-1}, measured by Fermi-LAT between 100 MeV and 100 GeV [2]. Although this result has aroused great interest in the scientific community, a single emitting zone can hardly account for the multi-wavelength observations and a opaque gamma-ray sources seems a viable scenario to describe IceCube and Fermi-LAT observations. NGC 1068 is one of the archetypical Seyfert 2 galaxies and its proximity (14.4 Mpc, [9]) makes it well-studied across the electromagnetic spectrum from radio to GeV produced by different emitting regions. To solve the discrepancy between observed neutrino and gamma-ray fluxes, a possible hadronic emission with a co-spatial gamma-ray absorption due to pair production has recently been attributed to the central magnetized corona of this AGN [6]. The typical size of the AGN corona is about $\gtrsim$ 10 Schwarzschild radii (Rs). Considering that high-energy particles can be accelerated in the corona, the nucleus of NGC 1068 is a plausible candidate for the flux of neutrinos observed by IceCube. In addition to that, sub-mm interferometry of molecular lines in the circumnuclear disk of NGC1068 ($\sim 200pc$ around the supermassive blackhole) suggests the presence of a AGN-driven outflow which can extend up to $\sim 100pc$ scale with a corresponding velocity of $\sim (100-200)km/s$ [5]. As reported in [8, 13] this outflow can induce shocks in the circumnuclear disk and accelerate relativistic charged particles with an efficiency even higher than the one in Supernova remnant (SNR) leaving a signature in different electromagnetic bands as well as in neutrinos. However as reported in [13] the resulted neutrino emission cannot account for the entire flux measured by IceCube collaboration from this Seyfert galaxy.

As other Seyfert galaxies, NGC1068 have also the peculiarity to be catalogued also as Starburst galaxy, with gamma-ray and infra-red luminosity following the quasi-linear relationship implying that a constant fraction of cosmic-ray energy in the nucleus can be converted into gamma-rays and neutrinos across the galaxy. Through the proportionality relation between infrared luminosity and star-formation rate introduced by [7] recent studies went through the possible hadronic emission from the core of NGC 1068 applying a calorimetric condition ($T_{loss} < T_{esc}$) to a small region of hundreds of parsecs. As reported in [4], even thought a sizeable fraction of observed gamma rays from NGC1068 can be attributed to the Starburst activity the neutrino counterpart is at the level of % respect to the flux measured by IceCube.

Interestingly NGC 1068 presents also kiloparsec-scale jet that translates into a linear dimension of 670 pc if an inclination angle of 45° is assumed. This jet has been resolved by several observations leaving at present mostly unexplored the correlated non thermal emissions. Atacama Large Millimeter/submillimeter Array (ALMA) observations at 100 GHz have recently reported parsec-scale magnetized (B 240 μ G) blobs at its head which seems preferential sites for relativistic electron-related emission. Moreover recent observations of a dense region at the end of the jet underline the possibility of hadronic interactions with correlated neutrino and gamma-ray emissions. In this proceeding we explore the leptonic, photohadronic and hadronic emissions possibly associated to this kiloparsec jet and we report the limits posed by the electromagnetic observations.

2. ALMA observations

The Atacama Large Millimeter/submillimeter Array (ALMA) reported observations of NGC 1068 at ~ 100 GHz, with low (~0.″4, 30 pc) and high resolution (~0.″05, 3 pc). From the low resolution map, a radio lobe with a kilo-parcec scale is notorious (hereafther NE-Lobe) [10]. When observed in the high-resolution ALMA map and using archival 15 GHz VLA data four blobs appear at the head of the NE-Lobe. The brightest blob is reported to have a diameter of ≈ 10 pc and a specific luminosity of $L_{92GHz} \approx 1.8\times10^{19}$ W Hz^{-1}. The presence of blobs indicates the formation of shocks from the interaction of the jet with the Interstellar medium (ISM).

Based on the ALMA observations, [14] report the enhancement of the magnetic field at the blobs. The emission is explained by synchrotron origin, reporting a minimum value for the magnetic field of $B_{min} \approx 240\ \mu G$, a value considerably higher when compared to those of the ISM.

Previous ALMA observations mapped dense molecular gas in the disk [5]. Using the kinematics of different tracers in the central region (r~ 2.8 kpc) of NGC 1068 they report densities for the molecular outflow of $n(H_2) \geq 10^{5-6}$ cm^{-3}.

NGC 1068 shows two prominent jets in the centimeter radio observations. The jet changes direction and it is presumed to be result from an interaction with a molecular cloud. The distance from the central black hole to the head of the jet is determined using data from the Very Large Array (VLA), which reports a size for the jet of $l_{\rm jet} \approx 670$ pc assuming an inclination of 45° respect to the line of sight and respect to the disk [5]. The jet has an estimated power of $P_{jet} = 1.8 \times 10^{43}$ erg s^{-1} based on observations in the 1.4 GHz band.

3. Electromagnetic components for the jet

3.1 leptonic contributions

Through ALMA observations we obtain the parameters used to modeling the leptonic emission. In particular we describe the electromagnetic spectral energy distribution (SED) reported in Fig. 2 through the Synchrotron Self Compton (SSC) emission produced by electron populations present in the four blobs reported in Fig. 1. The SSC contribution of Fig. 2 has been obtained through the use of AGNpy [12], an open-source python package modeling the radiative processes of relativistic particles accelerated in the jets of a AGN. From ALMA results [10] we get the values of doppler factor, bulk Lorentz factor, blobs dimension in the head of jet, angle respect to line of sight, magnetic field and the electron energy distribution used for the radiative processes computation. In Fig.2 the computed SSC emission considering the four blobs show different cases, varying the magnetic field up to a maximum value of 1200 μG, since [10] reported just a lower limit. In [10] the magnetic field lower limit is obtained assuming that magnetic and radio-emitting electron energy densities are close to the minimal value necessary to produce the synchrotron radiation observed; this correspond to a minimum value of 240 μG. Furthermore, radio analysis reveals a radio spectral

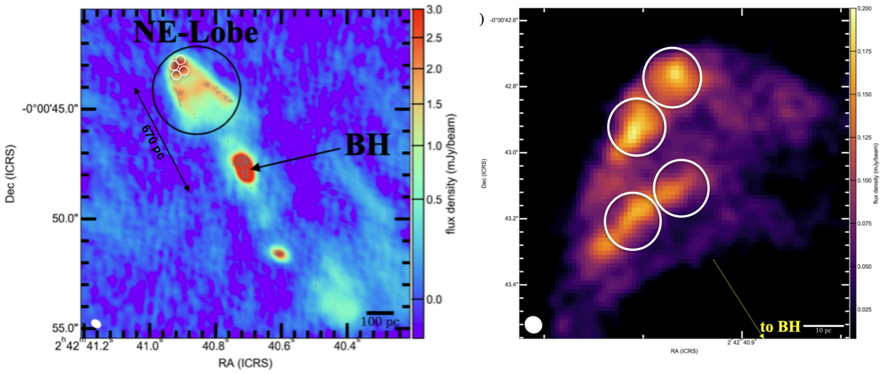

Figure 1: On the left ALMA low-resolution map at 93 GHz from [10] where the entire extension of the two jets are visible, in particular the one up to the north-est lobe with its 670 pc length. The solid black circle indicates the 4″ aperture while the small 4 white circles the represent the 4 resolved blobs. On the right enlarged views around the head of the NE-Lobe at the same frequency, with highlighted the 4 blobs with the diameter of 10 pc each. On the bottom right it is also reported the physical scale bar. aperture

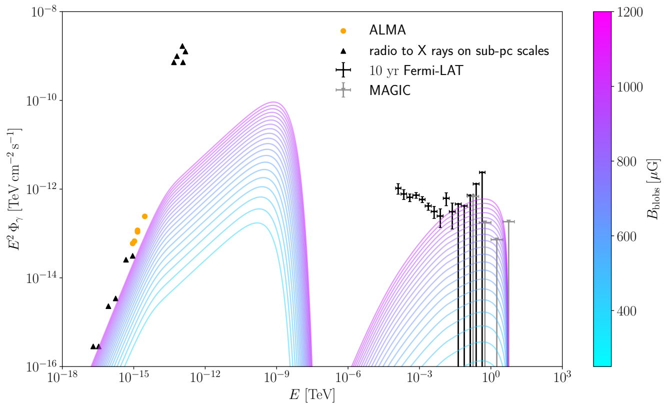

Figure 2: In this plot we report the EM spectral data from ALMA [6], VLT, Fermi-LAT [2] and MAGIC [3] and the computed SSC emission for the blobs at the head of the jet. We obtain the SSC components through AGNpy varying the magnetic field strength at the Blobs from $240\mu G$ up to $1200\mu G$.

index of $\alpha \approx 0.5$, which traduces in an electron energy spectral index of $p \approx 2$, consistent with what is expected from the diffusive shock acceleration (DSA) mechanism. In our analysis we set a upper limit for the magnetic field strength at each blob considering that the total electron emitting power at the blobs cannot exceed the total power of the jet,

$$P_e \approx \pi r_b^2 v_d U_e < P_{jet}/4. \tag{1}$$

With this condition we can assume values of the magnetic field up to $B \approx 1500$ μG. Nevertheless, further constrains can be set by gamma-rays produced due to π^0 decay in proton-proton (pp) interactions as showed in the next section.

4. Neutrino expectation

4.1 Photohadronic Emission

Taking into account the leptonic emission described in the previous section, we consider here the interactions of accelerated protons with the keV synchrotron photons at the blobs making them a potential photohadronic neutrino production sites. For this scenario, the neutrino spectrum can be estimated by

$$E_\nu^2 \frac{dN_\nu}{dE} \approx \frac{3}{8} f_{p\gamma} E_p^2 \frac{dN_p}{dE} \tag{2}$$

where $f_{p\gamma}$ is the photohadronic efficiency. This photohadronic efficiency can be estimated with the rectangular approximation to the photohadronic cross section as

$$f_{p\gamma} \approx \frac{t_{dyn}}{t_{p\gamma}} \approx \frac{2\kappa_\Delta \sigma_\Delta}{1+\beta} \frac{\Delta\bar{\varepsilon}_\Delta}{\bar{\varepsilon}_\Delta} \frac{3L^s_{rad}}{4\pi r_b \Gamma^2 c E_s} \left(\frac{E_p}{E_p^b}\right)^{\beta-1}$$

where $\sigma \approx 5 \times 10^{-28}\mathrm{cm}^2$, $\kappa_\Delta \approx 0.2$, $\bar{\varepsilon} \approx 0.34\mathrm{GeV}$, $\Delta\bar{\varepsilon}_\Delta \approx 0.2\mathrm{GeV}$, and $E_p^b \approx 0.5\Gamma^2 m_p c^2 \bar{\varepsilon}_\Delta / E_s$ [11]. For a magnetic field of 900 μG, the synchrotron luminosity becomes $L^s_{rad} \approx 2.2 \times 10^{-3}$ erg/s leading to a photohadronic efficiency of $f_{p\gamma} \approx 2 \times 10^{-7}$ for protons with $E_p \approx 1\mathrm{TeV}$. Additional to the maximum proton energy obtained by the arguments presented in section 3.2 of this work, we estimated the neutrino emission resulting from approximating the maximum proton energy using the Hillas condition,

$$E_{p,\max} = 3 \times 10^7 \mathrm{GeV} \frac{\mathrm{B}}{1\mathrm{G}} \frac{\mathrm{R}}{10^{10}\mathrm{Km}} \frac{\eta}{0.1}, \tag{3}$$

where B represent the magnetic field, R the region dimension and η the acceleration efficiency. Photohadronic production was computed considering both proton acceleration within the jet blobs and along the entire length of the jet. For the blobs we use a magnetic field of 900μG and a acceleration size equivalent to the radius of the blobs $R = 5$pc. Conversely, for the jet region, we set an average magnetic field strength of $50\mu G$ and consider the entire length of the jet of $R = 670$pc. We adopt an acceleration efficiency of $\eta = 0.1$ for both scenarios.

4.2 Hadronic Emission

As described in the EM emission section a major hadronic contribution from the observed kiloparsec jet of NGC1068 can be related to the interaction of CR accelerated in the jet with the dense gas material surrounding the jet region. As mentioned, several observations reported the presence of molecular gas at the end of jet region with variable density spanning from from $n(H_2) \geq 10cm^{-3}$ up to $n(H_2) \geq 10^{5-6}cm^{-3}$ [5]. While the related neutrino production can reach the flux level observed by IceCube last year [1] the corresponding gamma-ray emission would overshoot the Fermi-LAT and MAGIC observations. The level of possible gamma-ray attenuation due to pair production or Compton scattering seems not enough to produce a significant flux losses for the considered emitting volumes. Therefore the gamma-ray observations represent for this hadronic scenario the major bound for the flux of neutrino produced at the end of the observed kiloparsec

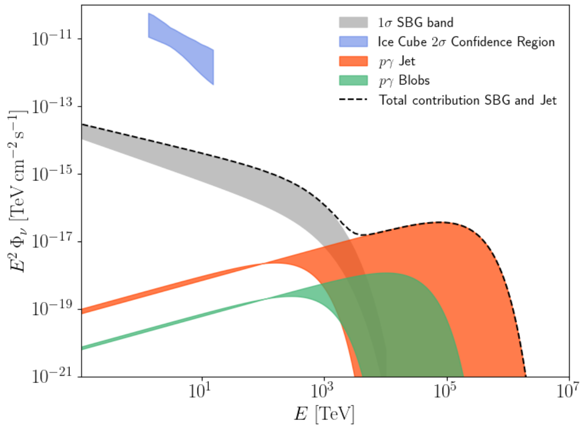

Figure 3: Neutrino spectra resulting from the interaction of accelerated protons with the synchrotron photon produced in the blob regions by electron populations. For the acceleration sites of protons we consider the same blobs (5 pc scale) as well as the entire jet (670 pc scale). The magnetic fields considered for the two regions are the following: (B_{blobs} = 900μG, $B_{ave,jet}$ = 50 μG). For both cases we apply two different E_{pmax}, the one obtained through the DST time and obtained through the Hillas condition (green and orange regions). In grey it is reported the 1σ neutrino spectral region obtained for the hadronic starburst activity of the central core of NGC1068 [4] The 2σ CR measured by IceCube for NGC1068 is reported for comparison. The sum of ν emission from SBG activity and photohadronic interaction in the jet of NGC1068 is at the level of % respect to the IceCube measurements mainly because of SBG emission which dominate over the two. The reported neutrino fluxes are per single family.

scale jet. To be consistent with the result of previous sections, we assume that accelerated protons interact in a hemisphere with a radius of 40pc (which corresponds to the aperture dimensions of the observed jet) located at the end of the 670pc jet. We consider a gas density of n = 10cm^{-3} for this interacting volume. Fig. 4 shows the neutrino SED for different values of the magnetic field considered. As can be seen in Fig. 4, with a magnetic field of 1200μG the pp interaction happening at the end of the Kpc jet is capable of explaining around 1% of the IceCube best fit at 1.5 TeV and around 15% of IceCube's best fit at 15 TeV. Nevertheless the hadronic components from the Kpc jet of NGC1068 could not be neglected when a multi-components scenario is considered.

5. Conclusions

Since November 2022, when the IceCube collaboration reported a 4.2σ neutrino excess from the direction of the Seyfert galaxy NGC1068 with 10 years of data, different scenarios has been introduced exploring the possible emitting regions. Explain the neutrino flux and the EM emission considering a single emitting region seems a challenging purpose. During the last years several studies focused on the AGN activity of NGC 1068 studied only the central few teens of pc. The neutrino emission from the magnetized corona and dusty torus regions as well as the possible hadronic emission from a hypothethycal UFO presence has been discussed recently. In this work we highlight the characteristics of another region of interest for neutrino emission, recently described through the data of ALMA observatory: a 670 pc jet with an angle of 45° respect to the line of sight, with luminous blobs observed at the head of the jet and a extended region of molecular gas

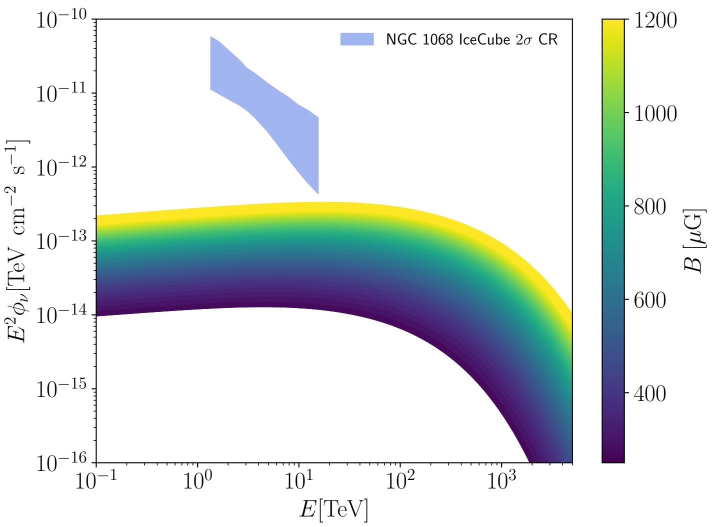

Figure 4: In this plot we report the expected neutrino emission from the interaction of accelerated protons in the jet with a hemisphere of radius of 40 pc considering the presence of a molecular gas with a density of n = 10 cm^{-3}. When considering a magnetic field of 1200 μG the computed neutrino emission at 15 TeV results to be at the level of 15% of the best fit of IceCube measured flux (reported here with the violet butterfly). We show the neutrino fluxes for $\nu_\mu + \bar{\nu}_\mu$.

around it. We computed the leptonic and hadronic contributions from the resolved blobs as well as from the entire jet. Here we show that the leptonic, photohadronic and hadronic contributions computed from these regions cannot be neglected when doing a multi-component description of the observed electromagnetic SED. While neutrinos produced by the photohadronic interactions seems negligible respect to the other mentioned emitting regions, the neutrinos produced through the interaction of jet-accelerated protons with the ambient molecular gas around the head of the jet produce a considerable flux. This flux results to be at the level of % respect to 1.5 TeV best-fit IceCube measurements and at the level of 15% respect to the 15 TeV best-fit IceCube observations. The obtained neutrino emission from the jet is well grounded on the detailed estimation of parameters from the recent ALMA work and suggest an additional softer neutrino component from the central part of NGC1068.

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