PROCEEDINGS OF SCIENCE

High Energy Neutrino Emission from Global Accretion Flows around Supermassive Black Holes

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The spectral energy distributions (SEDs) of the high energy neutrino emitted from the accretion flows are still highly uncertain, because the global structure of the accretion flow can affect the neutrino SEDs. We have computed high energy neutrino SEDs by using three-dimensional general relativistic magnetohydrodynamic (GRMHD) simulations data of a magnetized accretion flow around a spinning black hole. The SEDs of the nonthermal protons are calculated by solving the Fokker-Planck equation in the rest frame of the tracer-particles of protons. We assume the effects of the turbulent accelerations with the hard-sphere approximation and compression/expansion of the fluid elements. For the hadronic processes, we consider the effects of the pp collisions and subsequent high energy neutrino emissions taking into account the effect of the gravitational redshift. We have found that the neutrino SED become flatter than the previous 1 zone models because of the superposition of the neutrino SED emerged from the different position of the accretion flows.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

*Speaker

PoS(ICRC2023)1522

1. Introduction

The high energy neutrinos have been extensively studied in the context of the multi-messenger astrophysics, because, in particular, the astrophysical neutrinos will be a smoking gun of the high energy cosmic-ray accelerator [1]. The IceCube collaboration has detected the astrophysical diffuse neutrinos and hot spot [2], e.g., NGC 1068 (M77) [3, 4].

Active galactic nuclei are one of the candidates of the IceCube neutrino sources, where the cosmic-ray protons are suggested to be accelerated in accretion flows and/or coronae [5–10]. While the 1-zone approximation employed in the previous studies is useful to understand the fundamental features of the spectral energy distribution of the neutrinos and cosmic rays, the effects of the global structure of the underlying plasma will be also important.

In this study, we, therefore, compute the acceleration of the protons and the consequent spectral energy distributions (SEDs) of the high-energy neutrinos, by using three-dimensional general relativistic magnetohydrodynamic (GRMHD) data. In the section 2, numerical methods are discribed. In the section 3, we present the resulting SEDs of high-energy neutrinos and accelerated protons. We summarize our results in the section 4.

2. Method

We calculate the spectra of high-energy neutrinos emitted via the pp inelastic collision processes in accretion flows and outflows, by post-processing GRMHD simulation data. We set super-particles in the simulation domain, and trace the trajectory of particles on the streamliens of accretion flows and outflows of the GRMHD simulation. The protons are assumed to be stochastically accelerated by kinetic-scale plasma turbulence (i.e., sub-grid scale turbulence of GRMHD simulations) in accretion flows and outflows.

The time-dependent spatial distributions of MHD plasmas around a black hole are obtained by carrying out three-dimensional GRMHD simulations by using a GR-radiation-MHD code `UWABAMI` [14], where we turn-off the effects of the radiations, for the sake of the simplicity [15]. The dimensionless BH spin parameter is $a_* = 0.9375$. The set of GRMHD equations are integrated in the modified Kerr-Schild coordinate system (r, θ, φ). The resultant, dimensionless magnetic flux threading the event horizon $\phi_{\rm BH} = \Phi_{\rm BH}/\sqrt{\dot{M} r_{\rm g} c} \simeq 20$ in the CGS Gauss unit. Here, $\dot{M}_{\rm BH}$ and $\Phi_{\rm BH}$ are the mass accretion rate onto the black hole and the magnetic flux of the radial magnetic field threading the black hole, respectively. This state is sometimes called as "semi-MAD", which is the intermediate state between the SANE (Standard and Normal Evolution) [16] and MAD (Magnetically Arrested Disk) [16, 17]. We use the snapshot data in a quasi-steady state for the calculation of the acceleration of CR protons and subsequent neutrino emissions. We set the black hole mass $M_{\rm BH} = 10^8 M_\odot$ and the mass accretion rate $\dot{M}_{\rm BH} = 10^{-2} L_{\rm Edd}/c^2$, where $M_\odot$, $L_{\rm Edd}$, and c are the solar mass, the Eddington luminosity, and the speed of light.

The trajectories of the CR protons are calculated with a tracer particle method. We assume that the tracer particles move along the streamlines of GRMHD simulation snapshots by integrating the Fokker-Planck equation. The trajectories of the CR protons are traced until it is captured by the BH or escapes from the outer boundary of the computational domain. We employ the hard sphere approximation for the description of the diffusion coefficient. The injection rate of the

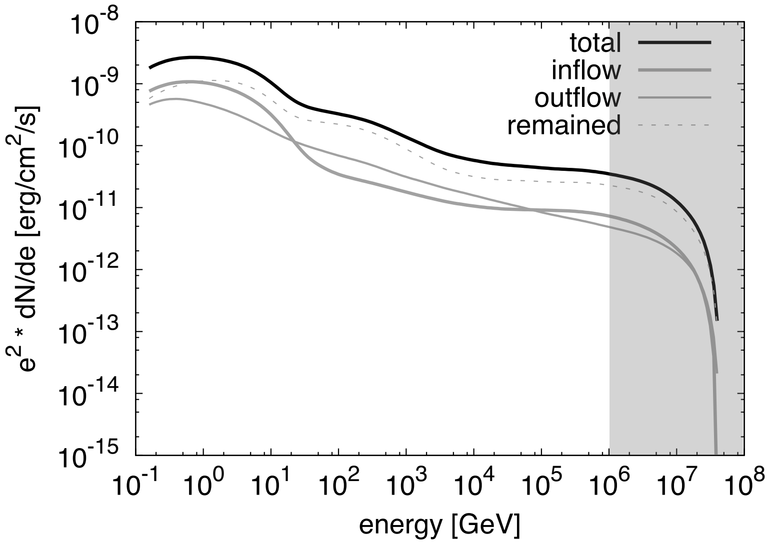

Figure 1: The relulting time-averaged neutrino SED. The total neutrino SED is presented by black solid line. The SED is decomposed into the emission from the proton which are captured by black hole (gray solid thick), escape to the observer (gray solid thin), and remains inside the simulation domain during the simulation (gray dashed thin). The energy range where our approximation of the tracer-particles moving along the stream lines are bached by light gray color.

cosmic-ray protons is assumed be proportional to the variation of the magnetic field strength along the trajectory the inverse of the plasma beta at each point, motivated by the magnetic reconnection. The Fokker-Planck equations are integrated based on the method using the Green function [11, 12].

We compute the emission of the high-energy neutrino via the pp colision between the accelerated protons of the tracer particle and the thermal protons of GRMHD snapshots, where the physical scale is given by the mass accretion rate. We use a fitting formula of the pion and resultant neutrino energy spectra as a function of the accelerated proton for pp collisions described in [13]. Finally. the observable neutrino SED is computed by taking into accoun the gravitational redshift.

3. Result

We demonstrate the resulting time-averaged neutrino SED in Figure 1. One may find neutrinos SED becomes flatter than those based on the turbulent accelerated 1-zone models. We decompose the neutrinos SED into the component originated by the accelerated protons which are finally captured by the black hole and escape to the observer. In this model parameter setup, the swallowed and escaped protons approximately equally contribute to the observable neutrino SEDs. One may also find that the remaining protons, which we find only $\sim 1\%$ in their number, significantly contribute to the neutrino SEDs. However, it will not affect our conclusion that the neutrino SEDs can become flatter than those based on the 1-zone models.

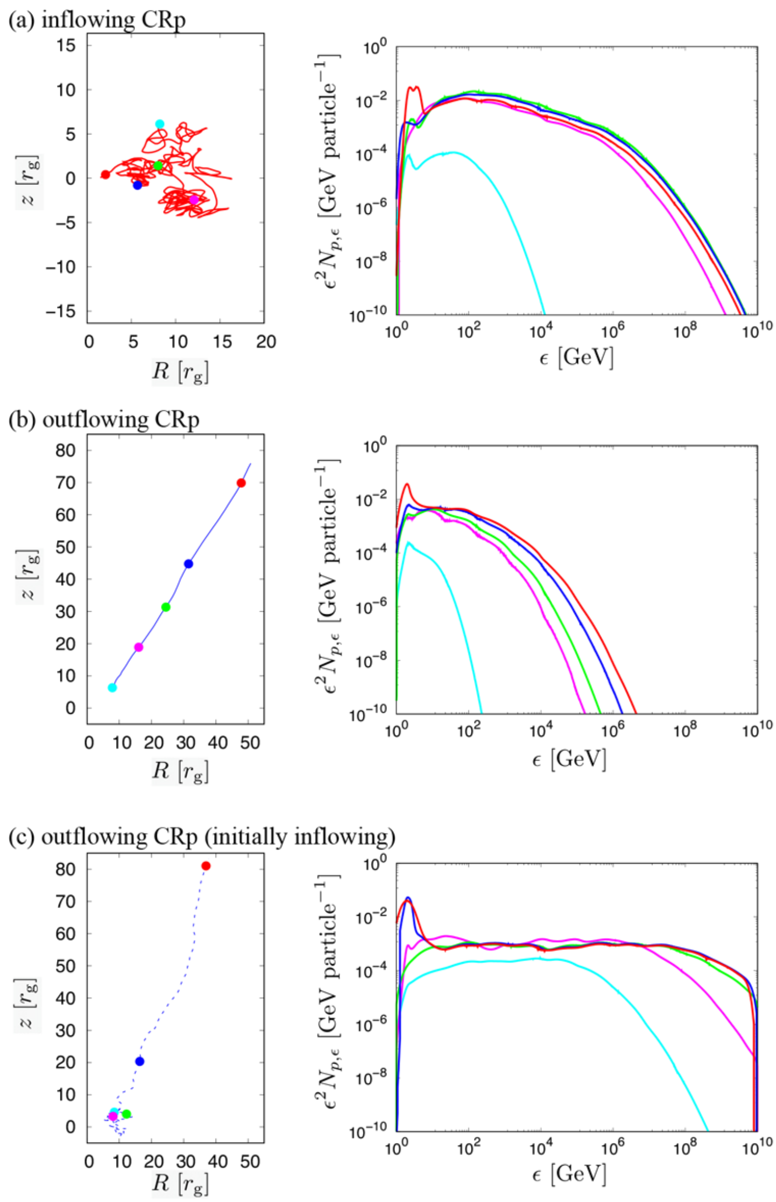

Figure 2: Left: The trajectories of tracer-particle of the cosmic-ray protons. Right: The SEDs of cosmic-ray protons at each location marked by the filled circles colored in cyan, magenta, green, blue, and red in the left panels.

The flatter features of the neutrinos SEDs in our model are attributed to the effects of the global acceleration of cosmic ray protons in the global accretion flow structure. Figure 2 shows the examples of the trajectories of the tracer-particle of the cosmic-ray protons and the accelerated proton SEDs. It is shown that the hardness of the proton SED depends on the trajectories of protons. For the case that the tracer-particle move inside the accretion flows during the long time, the protons are remarkably accelerated (top panels), since the acceleration timescale is shorter than the escape (i.e., being captured by black hole) timescale. On the other hand, when the tracer particles instantly becomes the outflows, the acceleration is less efficient (middle panels). It should be noted that the inflowing particles sometimes become the outflowing particles. In this case, the proton SEDs of the outflowing particle becomes remarkably hard since the particles are well accelerated during the inflowing phase (bottom panels). The proton SED depends on the trajectories and positions, and, therefore, the resulting neutrino SEDs become flatter attributed to the superposition of the various SEDs originated from the different protons.

4. Summary and Discussion

We have demonstrated the neutrino SEDs computed by assuming a turbulent accleration based on a global accretion flow model using GRMHD simulation data. It is found that neutrinos SEDs can become significantly flatter than those based on 1-zone models. The resultant flatter neutrinos SEDs will be consistent with the observation of the relatively flat SEDs of diffuse neutrino observed by IceCube [2].

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