Relativistic Jets Driven by Antielectron Neutrinos

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Abstract

The massive accretion disk producing a gamma-ray burst is investigated on the bases of the microphysics of neutrinos and the generalrelativity. The accreting matter is consists of heavy nuclei, free nucleons, degenerated electrons, photons and neutrinos. The fractions of leptons are calculated by using the network of lepton reactions. It is shown that the electron neutrinos are almost trapped in the massive accreting disk with the accretion rate, while the antielectron neutrinos penetrate through the disk and a large quantity of antielectron neutrinos with the large luminosity is ejected from the disk. The fraction of free neutrons per an unit number of baryons, and that of anti-electron neutrinos, increase to be, at the inner disk, while the fractions of free protons and electron neutrinos decrease to be infinitesimal. The cooling by the antielectron neutrinos produces the geometrically thin disk with great density and somewhat low temperature where the scattering optical depth and the degeneracy of the antielectron neutrinos become large. The high mean energy of the antielectron neutrinos and the large luminosity emitted from the accretion disk around a rapidly rotating black hole could drive the out flow, "neutrino driven jets", from the disk.

Key words: gamma rays: bursts — neutrinos — accretion, accretion disks — black hole physics — jets

1. Information

In the widely believed model of gamma-ray bursts, the high-energy emission arises in the relativistic jets ejected from a central engine. The formation of a relativistic jet has been investigated in two ways. One is owing to magnetic field. The rotating magnetized compact objects with matter accretion can generates strong toroidal magnetic fields driving highly magnetized plasmas into relativistic jets5.. The other is owing to neutrinos. The $\nu\bar{\nu}$-annihilation near accreting black holes can rise the energy deposition in the close vicinity of the black holes by the reactions, $\nu+\bar{\nu} \rightarrow e^{+}+e^{-} \rightarrow \gamma+\gamma$. The resulting $e^{+}e^{-}-$ pair plasma-photon fireball can power a relativistic outflow of baryons. However, it has been showed in the model of GRBs that most of neutrinos are trapped in accreting matter falling into a black hole 5. 5.. Nevertheless, it should be recognized first that the interaction of heavy nuclei with ambient free nucleons, which has been ignored in the previous works, produces rich free neutrons and rare free protons in high dense matter. The gradual viscous heating of a standard accretion disk (STAD) with Keplerian angular momentum maintains the disk to be relatively low temperature and to be in the domain of heavy nuclei. These different aspects in the massive accretion from the previous works produce the new thermal history of accreting matter and drive the neutrino ejection from the disk as a source of relativistic jets.

2. Microphysics of Accreting matter

In the previous works of ADAF, the free nucleons have been treated to be independent of heavy nuclei even in the dominant of heavy nuclei. We investigate here the neutrino reactions to the evaporated free nucleons interacting with heavy nuclei, where the chemical potentials of neutrons and protons, μ_n and μ_p, are equal in the two phase of evaporated free nucleon gas and the condensed heavy nucleus 5. 5.. It is shown that the accretion disk at the all region, $r_{in} \approx r_g < r \leq 10^2 r_g$, is cooled mainly by antielectron neutrinos, where r_g is the gravitational radius of a black hole. The massively accreting matter in STAD is in the domain of heavy nuclei all over the flow accreting onto a black hole. Therefore, the emitting rates of neutrinos are be precisely expressed in the existence of heavy nuclei. The profiles of density $\rho(\tilde{r})$ and temperature $T(\tilde{r})$, are expressed approximately as $\rho(\tilde{r}) \approx 2 \times 10^{14} \tilde{r}^{-2.5}\ \dot{m} m^{-2}$ g cm^{-3} and $T(\tilde{r}) \approx 5 \times 10^{10} \tilde{r}^{-1/4}\ m^{-1/3}$ K, where $\tilde{r}$ is normarized by gravitational radius r_g, $\dot{m}$ is normarized by $\dot{M}_{\odot}$ and m is normarized by $M_{\odot}$.

3. Degeneracy of Accreting Particles

The profiles of degeneracy factors of electrons $\eta_e(=\mu_e/kT)$, neutron-proton difference $\eta_{np}(=(\mu_n-\mu_p)/kT)$, degeneracy of antielectron neutrinos $\eta_{\bar{\nu}_e}$, electron neutrinos η_{ν_e} and heavy neutrinos η_{ν_x} are shown in Fig.1, where the accretion rate is taken as $\dot{M} = 1.0 M_{\odot}$ sec^{-1}

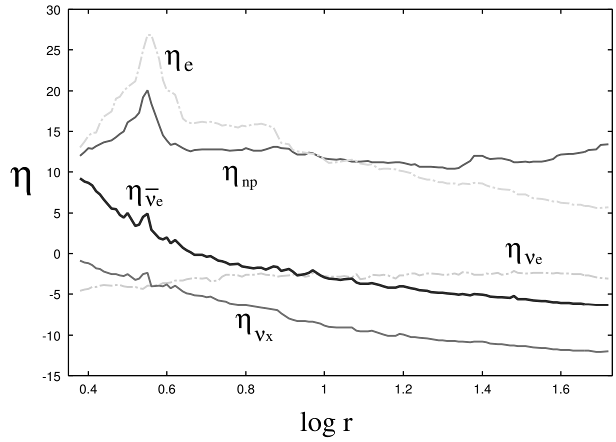

Fig. 1. The profiles of the degeneracy factors. The degeneracy factors of electrons $\eta_e (= \mu_e/kT)$, neutron-proton difference $\eta_{np} (= (\mu_n - \mu_p)/kT)$, degeneracy of antielectron neutrinos $\eta_{\bar{\nu}_e}$, electron neutrinos η_{ν_e} and heavy neutrinos η_{ν_x} are shown, where the accretion rate is taken as $\dot{M} = 1.0$M$_\odot$ sec^{-1} and the central mass of a black hole is M_{BH} =3M$_\odot$.

and the central mass of a black hole is M_{BH} =3M$_\odot$. The degeneracy of electrons η_e and that of neutron-proton difference η_{np} are very strong, $\eta_e \approx 5 \sim 25$ and $\eta_{np} \approx 10 \sim 20$. In the previous works in ADAF 5., the degeneracy of electrons is mild, $\eta_e \approx 1 \sim 3$. The number ratio of the free proton to the free neutron is proportional to the degeneracy factor,

$$\frac{n_p}{n_n} \approx \exp -\eta_{np} \approx 10^{-4 \sim -8}. \quad (1)$$

The free protons are strongly suppressed in the massive accretion disk with heavy nuclei.

4. Emissivities and Opacities of Neutrinos

The absorbing opacity of electron neutrinos $\kappa_a(\nu_e)$ is by far larger than those of other flavors of neutrino, $\kappa_a(\nu_e) \gg \kappa_a(\bar{\nu}_e) \geq \kappa_a(\nu_x)$. The electron neutrino ν_e is absorbed mainly by dense free neutrons through the reaction, $\nu_e + n \to e + p$, while the antielectron neutrino $\bar{\nu}_e$ is little absorbed by rare free protons, $\bar{\nu}_e + p \to e^+ + n$. The scattering opacities of $\bar{\nu}_e$ and ν_e are in same order, $\tau_{\bar{\nu}_e s} \approx \tau_{\nu_e s} \sim 10^2$. The antielectron neutrino acts as the most efficient source of emissivity. At the inner side of the disk, the emissivity by heavy neutrinos q_{ν_x} becomes efficient. The emissivity of electron neutrinos q_{ν_e} is one order of magnitude less than $q_{\bar{\nu}_e}$ since the proton fraction Y_p is infinitesimal. The emissivity of neutrinos rapidly increases along the flow. The total emissivity is expressed as $q = q_{\bar{\nu}_e} + q_{\nu_e} + q_{\nu_x} \approx 10^{35} \tilde{r}^{-4.25}$ erg cm^{-3} sec^{-1}. The flux density of antielectron neutrinos at the surface of the disk $F_{\bar{\nu}_e}$ rapidly increases along the accreting flow while that of electron neutrinos F_{ν_e} maintains almost the constant value. The ratio of the flux density of $\bar{\nu}_e$ to that of ν_e becomes large to be $F_{\bar{\nu}_e}/F_{\nu_e} \approx 10^{3 \sim 4}$ at the inside of the disk, since the electron neutrinos are almost absorbed by dense neutrons. The flux density of ν_x rapidly increases in the vicinity of the inner boundary and reaches to be comparable with $F_{\bar{\nu}_e}$. The total flux density is expressed as $F(r) = F_{\nu_e} + F_{\bar{\nu}_e} + F_{\nu_x} \approx 3.8 \times 10^{40} \tilde{r}^{-2.9}$ erg cm^{-2} sec^{-1} in the typical case of the accretion.

5. Luminosity and Mean Energy of Neutrinos

(1) The luminosity L_ν and the mean energy $\bar{E}_\nu$ are proportional to the specific angular momentum of a black hole, $L_\nu \propto a$ and $\bar{E}_\nu \propto a$. (2) The luminosity is proportional to the accretion rate, $L_\nu \propto \dot{m}$, but it is almost independent of the mass scale of a black hole, $L_\nu \approx$ *constant*, for $m = 1 \sim 10$. (3) The mean energy of neutrinos $\bar{E}_\nu$ is proportional the accretion rate while it is inversely proportional to the mass of a black hole, $\bar{E}_\nu \propto \dot{m}^{0.8} m^{-1.07}$. The typical accretion disk provides the luminosity, $L_\nu \sim 10^{52}$ erg sec^{-1}, and the mean energy, $\bar{E}_\nu \sim 20$MeV, which is several times larger than the thermal energy of a particle in the disk. This high mean energy $\bar{E}$ is caused by the large degeneracy, $\eta_{\bar{\nu}_e} \approx 5 \sim 10$. The energy flux, $L_\nu \sim 10^{52}$ erg sec^{-1}, with the mean energy, $\bar{E}_\nu \sim 20$MeV, emitted from a disk could produce the outward flow in the vertical direction to the disk. The huge neutrinos extract the thermal energy (liberated gravitational energy) in the disk and may play an important role in the formation of relativistic jets emitting γ-ray bursts.

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