Gamma-ray Emission from an Accretion Flow around a Kerr Black Hole

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Abstract

We calculate the spectrum of gamma-rays from a two-temperature advection-dominated accretion flow (ADAF) around a Kerr black hole, and examine the dependence of the gamma-ray intensity on the spin parameter of the central black hole. We consider gamma-rays produced through the decay of neutral pions created by proton-proton collisions in a hot ADAF. The temperature and density of ions in an ADAF vary according to the spin parameter, so does the intensity of the gamma-rays.

Since the energy distribution of ion particles in an ADAF is not known, we consider both thermal and power-law energy distributions of the protons. In the thermal model, we find that changes in the spin parameter in a range of -0.95 to 0.95 enhance the gamma-ray intensity by orders of magnitude. Thus, if the proton gas in an ADAF has a thermal distribution, the gamma-ray spectrum can be used as a probe to investigate the spin parameter of the central black hole. In the power-law model, on the other hand, the gamma-ray intensity is much less sensitive to the changes in the spin parameter than in the thermal model.

1. Introduction

If a Kerr black hole exists in the universe, what can be the sign of its existence? Some AGNs show extremely strong Fe Kα lines with very broad red wings (e.g., Tanaka et al. 1995; Iwasawa et al. 1996). General relativity shows that increases in the spin parameter move the marginally stable orbit inward. Since the Fe Kα line is considered to be emitted outside the marginally stable orbit, such strongly smeared lines as caused by relativistic effects suggest the existence of near-extremal Kerr black hole. However, this model is based on the optically-thick accretion disk model, and therefore we cannot apply it to an optically-thin accretion flow. What can then be the sign of a Kerr black hole with

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an optically thin flow?

Here we consider a Kerr black hole surrounded by ADAF. An ADAF is geometrically thick, optically thin hot accretion flow with low radiative efficiency (Ichimaru 1977; Narayan & Yi 1994, 1995a,b; Abramowicz et al. 1995). In the ADAF model, the viscous energy generated is stored in the flow and advected inward, while it is radiated away locally in the standard accretion disk model (Shakura & Sunyaev 1973). The ADAF model assumes that the viscous heating mainly heats ions, while only a small fraction of the viscous energy is directly transmitted to electrons (but see e.g., Bisnovatyi-Kogan & Lovelace 1997). It is also assumed that the ions transfer only a small fraction of their energy to the electrons via Coulomb scattering. The radiation from an ADAF is primarily produced by the electrons. The gas in an ADAF forms a two-temperature structure with the ions being hotter than the electrons (Shapiro, Lightman, & Eardley 1976; Rees et al. 1982).

The spectrum of an ADAF is mainly determined by the cooling processes of electrons such as synchrotron, bremsstrahlung, and Compton processes. Mahadevan, Narayan, & Krolik (1997), however, pointed out that the ion temperature in an ADAF close to a black hole is so high ($T_i \sim 10^{12}$ K) that gamma-rays are produced through the decay of neutral pions, which are created by proton-proton (p-p) collisions. They showed that once the spectrum produced by the electrons is fixed, which means that all the parameters in an ADAF are determined, the gamma-ray spectrum can be calculated uniquely. They, however, considered only the case of Schwarzschild black hole, and thus did not consider the spin of the central black hole. Manmoto (2000), on the other hand, studied the ADAF spectrum around a Kerr black hole by considering only the cooling processes of electrons. He showed that changes in the spin parameter affect differently the ion temperature and the electron temperature. Thus if we take full advantage of the gamma-ray spectrum, which contains information on the ion temperature, as well as spectrum in other bands, which contains information on the electron temperature, we can give constraints on the spin parameter of the black hole. In this paper we investigate whether the gamma-ray spectrum can be a probe for the spin parameter.

2. Model

2.1. Gamma-ray Emission Mechanism

In the ADAF model, the dissipated energy is stored in the accretion flow and advected inward. Since ions hardly radiate, they are heated near to the virial temperature. However, the ion temperature in the vicinity of a central black hole is so high ($T_i \sim 10^{12}$K) that p-p collision produces a neutral pion, π^o, which then decays into two gamma-ray photons (Mahadevan et al. 1997).

The emergent luminosity and shape of the gamma-ray spectrum dramatically depend on the proton energy distribution. The energy distribution function is determined by the mechanism of viscous heating. At present, the mechanism in an ADAF is, however, not well understood, and therefore it is not known whether the viscous heating leads to a thermal or a nonthermal distribution of proton energies (see Mahadevan & Quataert 1997). In order to calculate the π^o spectrum we assume two different proton energy distributions: a thermal distribution (e.g., Dermer 1986; Mahadevan et al. 1997) and a power-law distribution (Mahadevan et al. 1997; Mahadevan 1999). Details of the calculations of the gamma-ray spectrum are described in Oka & Manmoto (2002).

2.2. Calculation of ADAF

The structure of an ADAF is determined by the following parameters: the viscous parameter α, the ratio of the gas pressure to the total pressure β_p, the mass of the central black hole M, the mass accretion rate $\dot{M}$, the fraction of the viscous heating that goes into electrons δ, and the spin parameter $a(-1 < a < 1)$. A positive (negative) a means that the black hole corotates (counterrotates) with the accretion flow.

In the calculation of the ADAF structure, the ion particles are assumed to be thermalized, and therefore we obtain the ion temperature at each radius. For the nonthermal model we then redistribute the energy of the ion particles with the total energy at each radius fixed. We assume that the electrons are always thermalized by action of self-absorbed synchrotron photons (Mahadevan & Quataert 1997).

3. Results

We show the results obtained for the case of a typical AGN-mass black hole, $M = 10^8 M_\odot$. The mass accretion rate is $\dot{M} = 10^{-3}\dot{M}_c$, where $\dot{M}_c$ is the Eddington mass accretion rate. We set other parameters as $\alpha = 0.1$ and $\beta_p = 0.5$, which are typical values. We also assume that almost all the dissipated energy heats the ions by setting $\delta = 0.001$, although the determination of the value of δ is still a controversial issue (see e.g., Bisnovatyi-Kogan & Lovelace 1997). Using the ADAF+Kerr model (Manmoto 2000), we obtain the structure of the flow, and then calculate the gamma-ray spectrum. Here we do not take into account the Doppler and gravitational shifts, or the bending of the photons path.

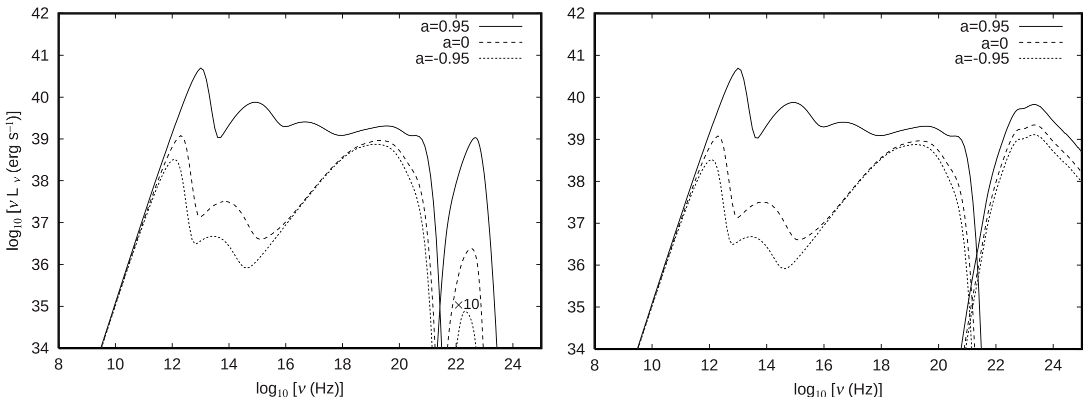

Fig. 1. *Left*: Spectra in the thermal model for $a = 0.95$ (solid lines), 0 (dashed lines), and -0.95 (dotted lines). Gamma-ray spectrum due to the pion-decay is located at frequencies higher than $\nu{\sim}10^{21}$ Hz. For $a = -0.95$ (dotted lines), the actual gamma-ray part of the spectrum is 10 times lower than shown. *Right*: Spectra in the power-law model with $s = 2.75$.

3.1. Thermal Model

The left panel of Figure 1 shows the spectra from the radio band to the gamma-ray band for $a = -0.95$, 0, and 0.95. Spectrum due to the pion-decay is located at frequencies higher than $\nu \sim 10^{21}$ Hz, while the spectrum due to the electron cooling processes such as synchrotron, bremsstrahlung, and Compton processes appears at frequencies lower than $\nu \sim 10^{21}$ Hz. We can see that the gamma-ray intensity is enhanced by orders of magnitude when the spin parameter changes from -0.95 to 0.95.

Next we assume that the spectra due to electron cooling processes have the same intensity at an X-ray point (1 keV). To do this, we adjust the mass accretion rate for the models with $a = -0.95$ and 0.95 to be $\dot{M} = 1.03{\times}10^{-3}\dot{M}_c$ and $5.8{\times}10^{-4}\dot{M}_c$, respectively. Although the corresponding spectra are not shown here due to limitation of space, it is found that even if the mass accretion rates are moderately changed, the gamma-ray intensity is enhanced by orders of magnitude when the spin parameter changes from -0.95 to 0.95. Based on the calculation, we can conclude that if proton gas in the ADAF has a thermal distribution, the gamma-ray spectrum can give a constraint on the spin parameter of a central black hole.

3.2. Nonthermal Model

We set the power-law index s of the power-law distribution to be 2.75. Other parameters are the same as in the case of the thermal model. The right panel of Figure 1 shows the spectra in the nonthermal model. We find that the variation of the gamma-ray intensity is less than a factor of 10 when the spin parameter increases from -0.95 to 0.95. The gamma-ray spectrum in the power-law model is much less sensitive to changes in the spin parameter than in the thermal model.

We also calculate the spectra in the nonthermal model with the mass accretion rates adjusted as described in the previous subsection. We find that changes in the spin parameter have little effect on the gamma-ray intensity. Thus we conclude that it is difficult to estimate the spin parameter from the gamma-ray spectrum if the energy distribution of ions in the ADAF is nonthermal.

4. Summary and Discussion

We investigate the dependence of the gamma-ray spectrum from an ADAF on the black hole rotation and examine whether the gamma-ray spectrum can be a probe to investigate the spin parameter.

Since the mechanism of viscous heating in the flow is not well understood, we adopt two different proton energy distributions: a thermal distribution and a power-law distribution. In the thermal model, we find that changes in the spin parameter from -0.95 to 0.95 enhance the gamma-ray intensity by orders of magnitude. Therefore if the proton energy distribution is thermal, we can estimate the spin parameter from the gamma-ray spectrum using the multi-wavelength observations. In the power-law model, on the other hand, the gamma-ray spectrum is much less sensitive to changes in the spin parameter than in the thermal model, and thus it is not easy to estimate the spin parameter from the gamma-ray spectrum.

Are there any suitable objects to be tested with our model? The spectrum of a black hole candidate at our galactic center, Sgr A*, has been explained naturally with the ADAF model (Narayan, Yi & Mahadevan 1995; Manmoto, Mineshige, & Kusunose 1997; Narayan et al. 1998; Manmoto 2000; Narayan 2002). Although there are several objects whose spectra are explained by the ADAF model, Sgr A* is the only object whose gamma-ray intensity is above the detection threshold of EGRET (Mahadevan et al. 1997). The comparison of our model with Sgr A* will appear soon (Oka & Manmoto 2002). Mahadevan et al. (1997) showed that some other sources would be detected by the next generation gamma-ray telescope, GLAST. Comparison of our model with these future gamma-ray observations could reveal the spin parameter of these black holes.

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