SPINS OF THE SUPERMASSIVE BLACK HOLE IN M87: NEW CONSTRAINTS FROM TeV OBSERVATIONS

JIAN-MIN WANG,†,‡ YAN-RONG LI,† JIAN-CHENG WANG,† and SHU ZHANG†

Received 2007 December 6; accepted 2008 February 21; published 2008 March 6

ABSTRACT

The rapid TeV γ-ray variability detected in the well-known nearby radio galaxy M87 implies an extremely compact emission region (∼5–10 Schwarzschild radii) near the horizon of the supermassive black hole in the galactic center. TeV photons are affected by dilution due to interaction with the radiation field of the advection-dominated accretion flow (ADAF) around the black hole, and can thus be used to probe the innermost regions around the black hole. We calculate the optical depth of the ADAF radiation field to the TeV photons and find it strongly depends on the spin of the black hole. We find that transparent radii of 10 TeV photons are of 5Rg and 13Rg for the maximally rotating and nonrotating black holes, respectively. With the observations, the calculated transparent radii strongly suggest the black hole is spinning fast in the galaxy. TeV photons could be used as a powerful diagnostic for estimating black hole spins in galaxies in the future.

Subject headings: black hole physics — galaxies: individual (M87)

1. INTRODUCTION

It is generally accepted that accretion onto supermassive black holes (SMBHs) is the major source of their growth during the periods of active nuclei duty cycles (Chokshi & Turner 1992; Yu & Tremaine 2002; Marconi et al. 2004; Wang et al. 2008). This process spins up the SMBHs, with the result that most SMBHs should be rapidly rotating (Bardeen 1970; Thorne 1974; Volonteri et al. 2005; Wang et al. 2006). The only strong evidence for rapidly rotating individual extragalactic SMBHs is the gravitationally broaden profile of the iron Kα line in the X-ray spectrum of MCG −6−30−15 (Wilms et al. 2001; Fabian et al. 2002; Brenneman & Reynolds 2006). The general lack of observational evidence for gravitationally broadened iron Kα lines leaves the issue of black hole spin as one of the most elusive questions in astrophysics.

It is well known that M87 (at a distance of ∼16 Mpc) contains an SMBH with a mass of $M_\bullet = (3.2 \pm 0.9) \times 10^9 M_\odot$ based on observations with the Hubble Space Telescope (Harm et al. 1994; Macchetto et al. 1997). Thanks to the high spatial resolution of these observations, structures in the core of M87 have been resolved on scales of 20 pc at optical wavelengths (Harm et al. 1994) and ∼100Rg in radio wavelengths (Junor et al. 1999), where $R_g = 2GM_\bullet/c^2$ is the Schwarzschild radius, $G$ the gravitational constant and $c$ the light speed. The multiwavelength continuum can be explained by a simple ADAF or modified model with outflows under a Schwarzschild hole (Di Matteo et al. 2000, 2003). Several parameters in these models are strongly degenerate; it remains an open question whether the SMBH is rapidly rotating.

The goal of the present Letter is to estimate the SMBH spin based on the TeV variability detected in M87 by the High Energy Stereoscopic System (HESS) (Aharonian et al. 2006). An origin from jet has been ruled out (Aharonian et al. 2006). The attenuation of TeV photons by the ADAF radiation field depends on the spectral energy distribution (SED) along the ADAF radius. This presents us with the opportunity to tackle this issue.

2. ADVECTION-DOMINATED ACCRETION FLOW IN M87

Figure 1 shows the multiwavelength continuum of M87. From radio to X-rays, the SED is dominated by emission from the accretion flow around the SMBH (Di Matteo et al. 2003). The spectrum has a bolometric luminosity of $\sim 10^{41}$ erg s$^{-1}$, giving the accretion flow an Eddington ratio of $\sim 10^{-6}$. This implies that an advection-dominated accretion flow is at work in the galaxy (Reynolds et al. 1996; Di Matteo et al. 2003). For simplicity, we use a self-similar solution of the ADAF (Narayan & Yi 1994) to determine the temperatures of both protons and electrons (Narayan & Yi 1995) in order to calculate the emergent spectrum. The self-similar solution of the ADAF is characterized by a factor $f$, which describes the fraction of the released gravitational energy that is advected into the black hole. The tendency of $f \rightarrow 1$ has been verified by extensive numerical calculations of the global solution of the ADAF (e.g., Narayan et al. 1997; Mannmoto et al. 1997). We define $\dot{m} = \eta M c^2/L_{\text{Edd}}$, where $M$ is the accretion rate, $\eta = 0.1$ the radiative efficiency, and $L_{\text{Edd}}$ the Eddington luminosity. There are five parameters $\alpha$, $\beta$, $\dot{m}$, $M_\bullet$, $R_g$, in the ADAF model, where $\alpha$ is the viscosity, $\beta = P_g/(P_g + P_b)$ where $P_g$ and $P_b$ are the gas and magnetic pressures, respectively—and $R_g$ is the inner radius of the ADAF. We refer to Schwarzschild and Kerr holes as those with specific angular momentum $a = 0$ and $a = 1$, respectively, where $a = J/(GM_\bullet^2 c^{-1})$ and $J$ is the angular momentum of the hole. Spins are directly related to the inner radius $R_g$, which can be determined by fitting observed continuum. For Schwarzschild and Kerr holes, the inner radius $R_g = 6R_g$ and $R_g$, respectively, where $R_g = R_g/2$ is the gravitational radius. We begin by fitting the observed multicolor SED of M87 to determine the best-fit parameters of the accretion flow. Then we find the optical depth of the ADAF radiation to TeV photons. We include synchrotron, multiple Compton scattering, and free-free emission processes in these calculations. We follow the numerical scheme for the emergent spectrum described in Mannmoto et al. (1997) (see also Yuan et al. 2000) in this Letter.

We used the black hole mass measured by HST in fitting the continuum. The viscosity and advection factors of $\alpha$ and $f$ are actually absorbed into one parameter in the self-similar solution. Although the viscosity $\alpha$ is highly unknown, only their combination of $\alpha$ and $f$ is important for the SED model (Narayan & Yi 1995). The final optical depth to TeV photons is directly dependent on the radial SED rather than $\alpha$ and $f$, so we take typical values of $\alpha = 0.3$ and $f = 0.99$. The ADAF spectrum is characterized...
by a sharp peak of synchrotron emission from moderately relativistic electrons, multiple bumps from inverse Compton scattering, and a high energy peak with a cutoff originating from bremsstrahlung emission from the very hot plasma in the ADAF. The roles of $\beta$ and $\dot{m}$ are clear in fittings of the continuum (Narayan & Yi 1995) if the inner radius of the ADAF is fixed. For a plasma with equipartition between the gas and magnetic fields, $\beta_{eq} = 0.5$. For $\beta > \beta_{opt}$ the plasma is weakly magnetized and for $\beta < \beta_{opt}$ the plasma is strongly magnetized. Usually $\beta = 0.5$ works generally, but it needs to be elaborately adjusted for specific fittings. For a model with a fixed $R_{in}$, the synchrotron peak is primarily determined by $M_{\bullet}$ while the Compton bumps and X-ray peak are sensitive to $\dot{m}$ and $\beta$. Figure 1 shows the best-fitting ADAF models with $R_{in} = 1R_{g}$ and $6R_{g}$. The Kerr model, with $\beta = 0.35$ and $\dot{m} = 5.5 \times 10^{-3}$, is consistent with the entire spectrum from radio to X-rays, while the Schwarzschild model with $\beta = 0.35$ and $\dot{m} = 2.0 \times 10^{-3}$ can match the data at only radio, near-IR, and optical wavelengths, but not always with the X-ray data. The differences between the two models originate from the fact that the Kerr black hole has higher radiation efficiency than the Schwarzschild. For the same total luminosity, the accretion rate is lower for the Kerr hole than the Schwarzschild, resulting in a thinner medium of the accreting gas and then reduced free-free emission in X-ray band. We note, however, that modified models of the ADAF might in principle produce a variety of spectra (Di Matteo et al. 2003) and that measurements of the SMBH spins strongly depend on $\dot{m}$. We present a new method for revealing the SMBH spin using the constraints from TeV variability.

Uncertainties in the ADAF model fit results are primarily governed by $\dot{m}$ and $R_{in}$ for models with fixed $\alpha$ and $f$. In particular, the modeled X-ray spectrum strongly depends on both $\dot{m}$ and $R_{in}$. It is difficult to estimate these uncertainties; however, the upper limit of $R_{in}$ will be constrained by the upper limit of the region responsible for the observed TeV variability.

3. OPTICAL DEPTH OF TeV PHOTONS AND THE HOLE’S SPINS

We calculate the number density of soft photons from the ADAF as a function of position $P(R, \Theta, 0)$. Figure 2 shows the geometric scheme for the ADAF disk. The vertical structure of the ADAF is unknown, but it is generally assumed that the vertical density has an exponential profile (e.g., Manmoto et al. 1997). We follow this with the assumption that most of the emitted photons originate from the midplane of the accretion
disk. With simple manipulation, we have \( \cos (\text{POD}) = \sin \Theta \cos \phi \), and the distance

\[
d^2_D = R^2 + R_0^2 - 2RR_0 \sin \Theta \cos \phi. \quad (1)
\]

The cosine of the angle between two interacting photons is then

\[
\mu = \frac{R - R_0 \sin \Theta \cos \phi}{d_D}. \quad (2)
\]

We then have the number density of photons from the ADAF, given by

\[
n_m(\Theta, R, \epsilon, R_D) = \frac{F(R_D, \epsilon)}{2\pi d_D^2 \epsilon m_e c^3} \left( \frac{R}{d_D} \right) \cos \Theta, \quad (3)
\]

where \( F(R_D, \epsilon) \) is the upper stream flux of photons from a radius \( R_D \), the factor of \( (R/d_D) \cos \Theta \) is the projected area element in the direction DP, \( m_e \) is the mass of the electron, and \( \epsilon \) is the photon energy in units of \( m_e c^2 \).

Figure 3 shows the SEDs for both Kerr and Schwarzschild black holes at four and three different radii, respectively. The SEDs demonstrate that gravitational energy is dissipated in a more compact region for a Kerr hole than a Schwarzschild. This is the key point that provides an opportunity to probe the black hole spin. We stress here that we neglect general relativistic (GR) effects in this Letter; however, the release of gravitational energy via viscous dissipation will be concentrated in a more compact region if we include the effects. This, in fact, increases the robustness of the conclusions presented here. More sophisticated models including GR effects will be given in a future paper.

TeV photons can divulge details of the ambient radiation field through their dilution via pair production. Pair production cannot be avoided if energies of two colliding photons \( \epsilon_1 \) and \( \epsilon_2 \) (in units of \( m_e c^2 \)) satisfy the relation

\[
\epsilon_1 \epsilon_2 = \frac{2}{(1 - \mu)(1 - v^2)}, \quad (4)
\]

where \( \mu \) is the cosine of the angle between the two photons, and \( v \) is the velocity of the positrons and electrons in the center-of-momentum frame in the units of \( c \). The optical depth of the radiation field to TeV photons can be obtained by integrating over the radius \( R \) along the propagation path of the TeV photons to infinity and the direction of incident soft photons, i.e.,

\[
\tau_{\gamma\gamma}(\Theta, R, \epsilon) = \int_R^\infty \int_{R_0}^{R_{\text{out}}} R dR_0 dR \int_0^{2\pi} d\phi \int_{\epsilon_{\text{in}}}^{\epsilon_{\text{out}}} d\epsilon' \sigma_{\gamma\gamma}(\epsilon', \epsilon', \mu) \times n_m(\Theta, R, \epsilon', R_D). \quad (5)
\]

where \( \sigma_{\gamma\gamma}(\epsilon', \epsilon', \mu) \) is the cross section of the two colliding photons (Gould & Schröder 1967), \( \epsilon_1 \) is the threshold energy of the interacting photons, and \( R_{\text{out}} \) is the outer radius of the ADAF. It should be noted that \( \tau_{\gamma\gamma} \) strongly depends on the incident angle between the two photons.

The dependence of \( \tau_{\gamma\gamma} \) on \( R_{\text{in}} \) (and thus the SMBH spin) can be qualitatively predicted. For a given bolometric luminosity, most of the gravitational energy dissipated during accretion onto a rapidly black hole is released in a more compact region than in a system containing a Schwarzschild black hole. This leads to a much steeper \( \tau_{\gamma\gamma} \rightarrow R \) relation around the Kerr black hole horizon and facilitates the escape of TeV photons from considerable smaller radii. It is thus expected that the timing information from TeV photons can be used as a diagnostic of the spatial distributions of the soft photon field surrounding the SMBH and thus its spin.

Figure 4 shows the optical depth of the radiation field to 10 TeV photons for the best-fitting ADAF models for both Schwarzschild and Kerr black holes. We fix \( R_{\text{out}} = 10^3 R_s \). We note that the final results are not sensitive to \( R_{\text{out}} \); \( \tau_{\gamma\gamma} \) is sensitive.
to radii, but not to the viewing angle. As we argue qualitatively, Figure 4 shows that the $\tau_{\gamma} - R$ relation is much steeper for Kerr holes than the Schwarzschild. For TeV photons to be able to escape from the radiation field of the ADAF, we require $\tau_{\gamma} \leq 1$. We define the transparent radius $R_t$ as the radius at which $\tau_{\gamma} = 1$. We find $R_t \approx 11a$, and $26R_t$ for Kerr and Schwarzschild black holes, respectively. The TeV variability timescale in M87, observed by HESS, is of ~2 days, implying a compact emission region of $R_{\text{TeV}} \leq cD_{\text{TeV}} \approx 10\,D_R$, where $D = 1/\Gamma(1 - V \cos \Theta/c)$ is the Doppler factor and $\Gamma = [1 - (V/c)^2]^{-1/2}$ the Lorentz factor of a jet with a velocity of $V$. If the jet is viewed at $\Theta = 30^\circ$ (Bicknell & Begelman 1996; Aharonian et al. 2006), the maximum Doppler factor is $D_{\text{max}} = 2$. Even if the TeV photons are emitted from the base of the relativistic jet, we have $R_{\text{TeV}} \leq 20D_R$, where $D_2 = D_{\text{max}}/2$. On the necessary condition of $R_{\text{TeV}} \geq R_t$, the HESS observations suggest the presence of a rapidly rotating black hole in M87 in terms of $R_t = 26R_t > R_{\text{TeV}}$ for a Schwarzschild black hole. Otherwise, the observed TeV region would be optically thick to 10 TeV. Increasing the black hole spin $a$, the transparent radius $R_t$ decreases. In order for the transparent radius to equal the TeV emission radius, we require a black hole spin of $a_{\text{TeV}} = 0.65$ for $m = 1.1 \times 10^{6}$. We note that the X-ray spectrum cannot be well fit with $a = 0.65$ and $m = 1.1 \times 10^{-7}$; however, we show the SED in Figures 1 and 4 to demonstrate how sensitive the transparent radius and the SED are to black hole spin. Figure 4 shows that in a region $1 \geq a \geq a_{\text{TeV}}$, in which the exact spins should be, black holes most likely have the maximum spin if the TeV region has a radius of $10R_t$.

We note that although the $\tau_{\gamma} - R$ relation becomes steeper with spin, $R_t$ is in fact insensitive to spins of $a < a_{\text{TeV}}$, making this technique less useful for estimation of their spins in slowly rotating black holes. The absence of any evidence for a potential break between 10 and 20 TeV means $\tau_{\gamma} \ll 1$ for these TeV photons, namely, the spin $a \geq a_{\text{TeV}}$. Otherwise, at $R = 10R_t$ for a Schwarzschild black hole, $\tau_{\gamma} \approx 5–6$ and the TeV photons will be attenuated by a factor of $e^{-\tau_{\gamma}} \approx 150–400$. This strongly conflicts with results from the TeV observations. The conclusion does, however, depend on the fitting of the multiwavelength continuum, which could be contaminated by other sources, for example, the inner jet. The current data and model do not allow us to constrain the spin to better than $a > 0.65$; however, future improved multiwavelength data and models will produce tighter constraints on how fast the spin is.

A rapid rotation is generally consistent with the statistic results from the Sloan Digital Sky Survey (Wang et al. 2006) and with justification from radio emission in term of the Blandford-Znajek effect (Newman et al. 2007). Since SMBH growth is primarily accretion, the spin angular momentum of the black hole is likely to be dominated by its accretion history. If the accretion is random, however, as suggested by King & Pringle (2007), the net spins of SMBHs should tend to zero. The spin evolution of SMBHs will thus uncover the accretion modes (corotating, retrograde, or random accretion) in their history from measuring spins of local SMBHs.

### 4. DISCUSSION AND CONCLUSIONS

The TeV variability as a new independent ingredient allows us to disentangle the inner radius from other parameters in modeling the multiwavelength continuum. We fit the multiwavelength continuum of M87 and use the best-fit parameters of the ADAF to calculate the optical depth of the ADAF radiation field to TeV photons. This optical depth is sensitive to the spin of SMBHs and combined with the TeV variability constraints, we conclude that the SMBH must be rapidly rotating in M87. Whatever mechanism produces the TeV photons in M87, these energetic photons provide a potentially powerful probe of the SMBH spin.

We should note some uncertainties in the present results, which fully depend on the theoretical model ADAF model, and contamination of the radiation in the central region from the host and jet. The influence of potential outflows from the ADAF should be examined in a future paper. Although we neglect the GR effects and the global structure of the ADAF in this Letter for simplicity, the addition of the effects will make the conclusion of this work robust, because the gravitational energy is dissipated in more compact regions due to the deeper gravitational potential than in the Newtonian case. The resulting $\tau_{\gamma} - R$ relation will then be steeper, reducing the transparent radius from which TeV photons can escape. Accurate measurements of the black hole spin rely on global calculations of the ADAF with general relativity and timescale measurements of TeV variability to confine the dimensions of the TeV region. Future observations of other sources with HESS may reveal TeV variability similar to that of M87, particularly in low-luminosity active galactic nuclei (LLAGNs), such as radio galaxies and low-ionization nuclear emission regions (LINERs). This would lead to further estimates of the spins of SMBHs in nearby galaxies. In addition, the present results suggest that any mechanism responsible for the production of TeV photons should be located outside a region with $\tau_{\gamma} \geq 1$, constraining the radiation mechanism of TeV photons.