SPECTRUM OF TWO-COMPONENT FLOWS AROUND A SUPERMASSIVE BLACK HOLE:
AN APPLICATION TO M87

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ABSTRACT

We calculate the spectra of two-component accretion flows around black holes of various masses, from quasars to nanoquasars. Specifically, we fit the observational data of M87 very satisfactorily using our model and find that the spectrum may be well fitted by a sub-Keplerian component alone, and there is little need of any Keplerian component. The nonthermal distribution of electrons produced by their acceleration across the standing shock in the sub-Keplerian component is enough to produce the observed flat spectrum through the synchrotron radiation.

Subject headings: acceleration of particles — accretion, accretion disks — black hole physics — galaxies: individual (M87) — hydrodynamics — shock waves

1. INTRODUCTION

The general view of the physics of the quasars and active galactic nuclei (AGNs) is that their energy output is due to accretion of matter onto a massive black hole (e.g., Blandford 1991; Antonucci 1993 and references therein). Analysis of the spectrum is very important in understanding the physical nature of the underlying flow. The observed spectral and timing properties of Galactic black holes indicate that the accretion flow around a black hole may have two components (Smith et al. 2001, 2002, 2007; Choudhury & Rao 2004; Pottschmidt et al. 2006): an optically thick and geometrically thin Keplerian accretion disk (Shakura & Sunyaev 1973) on the equatorial plane and an optically thin sub-Keplerian flow (Chakrabarti & Titarchuk 1995; Chakrabarti & Mandal 2006) sandwiching the Keplerian disk. The Keplerian disk produces a multicolor blackbody spectrum and the soft photons from the Keplerian disk are inverse-Comptonized by a hot electron cloud close to the black hole. The literature many proposals have been put forward for the Comptonizing region (Sunyaev & Titarchuk 1980, 1985; Haardt 1994; Poutanen & Svensson 1996) which range from a hot Compton cloud to a corona above accretion Keplerian disks. In a departure from this approach, Chakrabarti & Titarchuk (1995) proposed that both the so-called Compton cloud and soft-photon supplier are in fact dynamically important components. This model has a hot region produced due to a shock transition in the presence of the centrifugal force in the sub-Keplerian flow and is known as the CENBOL (CENtrifugal pressure supported BOundary Layer). In the present model, the CENBOL is responsible for producing the high-energy spectrum from an accretion disk. This two-component nature of the accretion disk can be treated as a general model where the accretion rates of both the components can be varied independently and the model should be applicable for all the black hole candidates (from the usual quasars and AGNs to nanoquasars or stellar-mass black holes). It is well known that the big blue bump in an AGN spectrum is the signature of the Keplerian disk and a number of spectra from the core of AGNs have been successfully fitted (Sun & Malkan 1989) by a standard disk model. On the other hand, an object such as M87 does not seem to have the big blue bump in its spectrum and one should require only a hot electron component, such as a sub-Keplerian flow, to interpret the observed spectrum. Fortunately, the same CENBOL component is capable of launching an outflow (Chakrabarti 1999) which manifests itself as a strong jet coming out of a region from within a few tens of Schwarzschild radii (Junor et al. 1999). The predicted profiles of the lines emitted from the sub-Keplerian component also seem to agree with observed profiles from HST (Chakrabarti 1995).

In this Letter, we calculate the spectra of two-component accretion disks around stellar-mass to supermassive black holes. This helps us to understand the basic functions of the components of the flow from a unifying view by varying only the mass. We then apply our model to the case of M87 by considering a purely sub-Keplerian disk around it. The Letter is organized in the following way: In § 2, we describe the model properties and the general nature of the spectrum. In § 3, we explain the spectrum of M87, and finally, in § 4, we present our concluding remarks.

2. MODEL PROPERTIES AND THE GENERAL NATURE OF THE SPECTRUM FROM A TWO-COMPONENT FLOW

We consider a vertically averaged two-component flow around a Schwarzschild black hole. The black hole geometry is described by a pseudo-Newtonian potential (Paczynski & Wiita 1980) and the vertical height of the accretion disk at any radial distance has been calculated by balancing the vertical component of gravitational force with the gas pressure (Chakrabarti 1989). The radial distance is measured in units of the Schwarzschild radius \( r_g = 2GM/c^2 \), where \( G \) is gravitational constant, \( M \) is the mass of the black hole, and \( c \) is the speed of light. The parameters of our model are the shock location \( x_s \), the compression ratio \( R \) of the shock (i.e., the ratio of the postshock to preshock densities), the fraction of electrons having nonthermal distribution of energy \( \xi \), and the accretion rates of the Keplerian \( \dot{m}_K \) and the sub-Keplerian halo \( \dot{m}_h \) components. The accretion rates are measured in units of the Eddington rates \( 0.2 M_{\odot} \text{ yr}^{-1} \) for a \( 10^8 M_{\odot} \) black hole. In the absence of a satisfactory description of magnetic fields inside the accretion disk, we consider the presence of only stochastic fields and use the ratio of the magnetic field energy density to the gravitational energy density to be a parameter \( \beta \). We have taken \( \beta = 1.0 \) throughout this Letter. The condition of the plasma at the outer boundary of the accretion disk is uncertain because the processes of feeding a black hole are not well

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known. It depends on the type of the donor star (Bath & Shaviv 1976) supplying matter in a compact binary or the condition of the ISM for AGNs. We have fixed the outer boundary at \( x_{\text{in}} = 10^3 r_g \). The injection temperatures of the electron and proton for a stellar-mass black hole are given by the adiabatic Bondi (1952) solution, i.e., \( T_{\text{in}} = 1.6 \times 10^5 \) K, which is consistent with the value found in the literature (Tavani & Brookshaw 1995). However, for AGNs, the outer boundary of the accretion disk could be cooler than that around a stellar-mass black hole as it contains the molecular or partially ionized gas. The temperature of the ionized gas lies in the range \( (1.0-1.7) \times 10^4 \) K (Wilson & Storchi-Bergmann 1997). As a example, we have taken the temperature at the outer boundary for a supermassive black hole as \( T_{\text{in}} = 1.6 \times 10^5 \) K. In the case of M87, the existence of an ionized disk has been discussed in the literature (Ford et al. 1994; Harms et al. 1994). In our model, we consider all the radiation processes, namely bremsstrahlung, synchrotron, and Compton scattering. Since the shocks are the natural outcome of a sub-Keplerian flow, we consider that the preshock electrons follow a pure thermal distribution while the postshock flow is a mixture of thermal and nonthermal electrons. This is because some electrons would be accelerated due to usual back and forth diffusion and compression across the shock (see Mandal & Chakrabarti 2005 and references therein). The slope \( \beta = (R + 2)/(R - 1) \) of the nonthermal distribution depends on the compression ratio \( R \) and it produces a synchrotron spectrum of power-law index \( \alpha = (1 - \beta)/2 \) with a sharp cutoff determined by the Lorentz factor \( \gamma \) of the accelerated electrons. We have taken this effect also in calculating the spectrum from the accretion disk.

AGNs are known to have very strong jets and in the core/nuclear region these jets are not separable from the accretion disk. So, the spectrum from the core will always have some contribution from the jet. There could be several hot regions which emit radio, optical, and X-ray radiation along the jet but these regions are separable from the nucleus. Understanding these high-energy emissions requires separate physical processes which are outside the scope of the present work. In our present calculation we are mainly interested the spectrum from the nucleus and have used a simplified model for the jet and added this contribution to the spectrum from the accretion disk. We have assumed that 10% of matter from the accretion disk is launched from the location of the CENBOL as a jet with the same temperature as that of the CENBOL. We have taken a cylindrical jet and solve the energy equations along the jet. The jet is assumed to cool down due to synchrotron emission.

In Figure 1 we show a typical accretion disk spectrum for a stellar-mass black hole (the so-called nanoquasar) to a supermassive black hole (quasar) with all the components computed from our model. The parameters are \( x = 20.0, R = 2.5, \xi = 0.01, \gamma = 2.7 \times 10^4, m_p = 0.5, m_e = 0.1 \). The contribution from the bremsstrahlung radiation is negligible for a stellar-mass black hole but it is significant for a supermassive black hole due to a lower temperature and larger emitting volume of the accretion disk. The preshock synchrotron radiation is huge for a stellar-mass black hole due to the large injection temperature whereas it is insignificant for a supermassive black hole. The Comptonized spectrum of the blackbody photons gets harder as the black hole mass increases. This is due to the fact that for the same value of accretion rate (in Eddington units) the density of the flow goes down with the mass and hence the optical depth of the flow decreases. But the Comptonized spectrum of the synchrotron photons becomes softer with the increase of the black hole mass. The ratio \( \epsilon \) of the photon energy density to the magnetic energy density represents the relative contribution of the inverse-Compton process. We find that for the stellar-mass black hole \( \epsilon = 0.26 \) whereas for the supermassive case \( \epsilon = 0.01 \) only. The jet, which is emitted from the CENBOL, can have a big contribution in the radio range for the supermassive case due to its large volume. So, the radio emission from the nucleus of the AGN will be contributed by the jets. We also note a frequency shift toward the lower end as the potential energy release itself decreases with increasing mass. Although generally speaking, the spectrum of a supermassive black hole will have all the components of that of a stellar-mass black hole, we show below that M87 could be fitted by considering a pure sub-Keplerian flow as it does not seem to have a so-called big blue bump. This was also noted by Perlman et al. (2001).

3. APPLICATION TO M87

The elliptical galaxy M87 contains a supermassive black hole of mass \( M = (3.2 \pm 0.9) \times 10^9 \) \( M_\odot \) (Macchetto et al. 1997) at the center and the inclination angle of the accretion disk with the line of sight is \( i = 42^\circ \pm 5^\circ \) (Ford et al. 1994; Chakrabarti, 1995). It is a low-luminosity AGN located in the Virgo Cluster at a distance of \( D = 16 \pm 1.2 \) Mpc (Tonry et al. 2001) having a prominent one-sided jet. The central luminosity of the accretion disk is \( \sim 10^{45} \) erg s\(^{-1} \) (Biretta et al. 1991) which is at least 2 orders of magnitude below the luminosity expected for a standard thin accretion disk accreting at the Bondi rate \( M_B = 0.1 \) \( M_\odot \) yr\(^{-1} \) (Di Matteo et al. 2003). In the literature, different explanations for the low luminosity of M87 have been given. The wave-particle resonance can efficiently couple the electrons and ions (Begelman & Chiueh 1988; Bisnovatyi-Kogan & Lovelace 2000; Quataert 1998; Quataert & Gruzinov 1999; Blackman 1999) to produce a geometrically thin cool disk. Jolley & Kuncic (2007) argued that this low luminosity is due to a thin cool disk accreting matter in a very low rate. On the other hand, if the coupling between electrons and ions is unable to equilibrate them within the infall
timescale and if the ions are preferentially heated by viscous dissipation, the accreting matter cannot radiate its internal energy before reaching the black hole. This leads to a radiatively inefficient accretion flow (RIAF) (Narayan & Yi 1994). According to this model the low luminosity is due to low radiative efficiency (Di Matteo et al. 2000) rather than a low mass accretion rate. But our approach is different from the above two in the sense that our accretion disk is neither a cool Keplerian disk, because the observation data shows a flat spectrum rather than a blue bump, nor a RIAF. Ours is simply a sub-Keplerian transonic flow (Chakrabarti 1990) which is equipped with a standing shock wave. This is fundamentally inefficient as the infall time is too short. The observed luminosity from the nucleus is likely to be less than the total accretion power because most of the energy is carried inside the black hole (in fact, a perfectly stable solution will exist even if the energy loss is zero) and rest is used to power the jet. In the case of M87 the total kinetic power of the jet is estimated to be \( \sim 2 \times 10^{46} \) ergs s\(^{-1}\) (Reynolds et al. 1996). Also, the jet is produced from a central region not more than a few tens of parsecs (Junor et al. 1999).

We have collected the broadband (radio, optical to X-ray) data from several previous works (Ho 1999; Reimer et al. 2004) in the literature. The details are given in Table 1. In Figure 2, we fitted these data by our model. We chose the parameters to be \( M = 3.2 \times 10^9 M_\odot \), \( \dot{m}_p = 10.0 \), \( R = 2.5 \), \( \gamma = 2.7 \times 10^2 \), \( \xi = 0.006 \), \( m_{\nu} = 0.3 \) to fit the data. The upper limit of the Keplerian disk rate is found to be \( \dot{m}_p = 0.001 \) for any decent fit. This indicates that the Keplerian disk is not important for M87 and the bulk motion Comptonization effect is negligible due to the small accretion rate required. The jet has a large contribution in the radio range due to high electron temperature and large volume. The low-energy data are well fitted by the thermal synchrotron radiation from the jet and the synchrotron emission produced by the cool preshock flow is insignificant. But the radio data (open triangles) which have a very high spatial resolution are very close to the preshock synchrotron spectrum. This radio contribution may be due to the accretion disk or it may be due the different observation epoch when the radio activity in the jet is very dim. The bremsstrahlung radiation has a small contribution only in the soft X-ray range. A shock of compression ratio \( R = 2.5 \) produces a nonthermal synchrotron spectrum of slope \( (\alpha + 1) \) which explains the flat part \( (\alpha + 1 = 0) \) for \( R = 2.5 \) of the observed spectrum. This is consistent with the previous finding that at this \( R \), the outflow rate is also most significant (Chakrabarti 1999). The sharp cutoff in the synchrotron spectrum is due to cutoff in the nonthermal distribution of electrons and it is determined by the value of \( \gamma \) mentioned above. The synchrotron self-Comptonized spectrum due to nonthermal electrons matches with the Chandra data which measures the core luminosity very accurately. We find the total bolometric luminosity of the nucleus as \( 9 \times 10^{42} \) ergs s\(^{-1}\). Most of the model of M87 are based on the emission from the jet only but we have shown that the spectrum from the nucleus can be under-

| \( \nu \) (log Hz) | \( \nu F_\nu \) (log Jy Hz) | Resolution (arcsec) | Instrument | Observation Year | Reference |
|------------------|--------------------------|---------------------|-------------|------------------|---------|
| 9.166 | 9.732 ± 0.016 | 1.2 | VLA | 1985 Mar 1 | 1 |
| 9.22 | 9.217 | 0.005 | VLA | 1984 Apr 6 | 2, 3 |
| 9.689 | 10.22 ± 0.01 | 1.2 | VLA | 1982 Mar 2 | 1 |
| 10.17 | 10.65 ± 0.01 | 1.2 | VLA | 1982 Mar 2 | 1 |
| 10.34 | 9.681 | 0.00015 | VLA | 1986 | 2, 4 |
| 11.0 | 10.94 | 0.00001 | VLA | 1989 Mar 23 | 2, 5 |
| 13.44 | 11.67 ± 0.02 | 0.5 | Gemini | 2001 May 3 | 6 |
| 14.13 | 11.49 ± 0.1 | 0.291 | UKIRT | 1994 Jun 4 | 7 |
| 14.378 | 11.767 ± 0.103 | 0.27 | ESO/LPI | 1993 May 31 | 7 |
| 14.78 | 11.79 ± 0.08 | 0.022 | FOC, HST | 1991 | 8 |
| 14.91 | 11.57 ± 0.08 | 0.022 | FOC, HST | 1991 | 8 |
| 14.958 | 11.204 ± 0.004 | 0.0284 | ACS, HST | 2003 Mar 31 | 9 |
| 15.07 | 11.146 ± 0.003 | 0.0284 | ACS, HST | 2003 Mar 31 | 9 |
| 15.11 | 11.31 ± 0.08 | 0.022 | FOC, HST | 1991 | 8 |
| 15.11 | 11.48 | 0.05 | FOC, HST | 1991 Apr 5 | 2, 10 |
| 15.28 | 11.11 ± 0.079 | 0.022 | FOC, HST | 1991 | 8 |
| 15.30 | 11.21 ± 0.079 | 0.022 | FOC, HST | 1991 | 8 |
| 15.38 | 11.59 ± 0.079 | 0.022 | FOC, HST | 1991 | 8 |
| 16.68 | 10.53 ± 0.06 | 0.54 | Chandra | 2000 Jul 20 | 11 |
| 17.38 | 10.92 ± 0.04 | 4.0 | HRI, Einstein Observatory | 1979 Jul 5 | 1 |
| 18.38 | 10.24 ± 0.08 | 0.54 | Chandra | 2000 Jul 20 | 11 |

References.—(1) Biretta et al. 1991; (2) Ho 1999; (3) Reid et al. 1989; (4) Spencer & Junor 1986; (5) Baith et al. 1992; (6) Perlman et al. 2001; (7) Stiavelli et al. 1997; (8) Sparks et al. 1996; (9) Maoz et al. 2005; (10) Maoz et al. 1996; (11) Perlman & Wilson 2005.
Fig. 2.—Fitting the spectrum of M87 nucleus using the shock solution of sub-Keplerian flow. The observational data are taken from Biretta et al. (1991; filled triangles), Ho (1999; open triangles), Perlman et al. (2001; open circle), Stiavelli et al. (1997; filled squares), Sparks et al. (1996; filled circles), Maoz et al. (2005; open squares), Perlman & Wilson (2005; Chandra). The dotted line (1) represents the preshock synchrotron contribution while the dot-long-dashed line (2) represents the bremsstrahlung contribution from the preshock flow. The short-dashed line (3) is due to postshock synchrotron contribution from nonthermal electrons. The long-dashed (4) and dot-dashed lines (5) represent the synchrotron self-Comptonized spectrum due to thermal and non-thermal electrons in the CENBOL. The long-short-dashed line (6) represents the synchrotron contribution from the jet.

REFERENCES

Antonucci, R. 1993, ARA&A, 31, 473
Baããth, L. B., et al. 1992, A&A, 257, 31
Bath, G. T., & Shaviv, G. 1976, MNRAS, 175, 305
Begelman, M. C., & Chiuheu, T. 1988, ApJ, 332, 872
Biretta, J. A., Stern, C. P., & Harris, D. E. 1991, AJ, 101, 1632
Bisnovatyi-Kogan, G. S., & Lovelace, R. V. E. 2000, ApJ, 529, 978
Blandford, R. D. 1991, Physics of Active Galactic Nuclei, ed. W. J. Duschl & S. J. Wagner (Berlin: Springer), 3
Bondi, H. 1952, MNRAS, 112, 195
Chakrabarti, S. K. 1989, ApJ, 347, 365
———, 1990, Theory of Transonic Astrophysical Flows (Singapore: World Scientific)
———, 1995, ApJ, 441, 576
———, 1999, A&A, 351, 185
Chakrabarti, S. K., & Mandal, S. 2006, ApJ, 642, L143
Chakrabarti, S. K., & Titarchuk, L. G. 1995, ApJ, 455, 623
Choudhury, M., & Rao, A. R. 2004, ApJ, 616, L143
Di Matteo, T., Quataert, E., Allen, S. W., Narayan, R., & Fabian, A. C. 2000, MNRAS, 311, 507
Di Matteo, T., et al. 2003, ApJ, 582, 133
Dopita, M. A., et al. 1997, ApJ, 490, 202
Ford, H. C., et al. 1994, ApJ, 435, L27
Haãrdt, F. 1994, Ph.D. thesis, SISSA, Trieste
Harms, R. J., et al. 1994, ApJ, 435, L35
Harris, D. E., Biretta, J. A., & Junor, W. 1997, MNRAS, 284, L21
Ho, L. C. 1999, ApJ, 516, 672
Jolley, E. J. D., & Kuncic, Z. 2007, ApèèSS, 311, 257
Junor, W., Biretta, J. A., & Livio, M. 1999, Nature, 401, 891
Macchetto, F., et al. 1997, ApJ, 489, 579
Mandal, S., & Chakrabarti, S. K. 2005, A&A, 434, 839
Maoz, D., Filippenko, A. V., Ho, L. C., Macchetto, F. D., Rix, H. W., & Schneider, D. P. 1996, ApJS, 107, 215
Maoz, D., Nagar, N. M., Falcke, H., & Wilson, A. S. 2005, ApJ, 625, 699
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
Paczyãñski, B., & Wiita, P. J. 1980, A&A, 88, 23
Perlman, E. S., Harris, D. E., Biretta, J. A., Sparks, W. B., & Macchetto, F. D. 2003, ApJ, 599, L65
Perlman, E. S., Sparks, W. B., Radomski, J., Packham, C., Fisher, R. S., Piãña, R., & Biretta, J. A. 2001, ApJ, 561, L51
Perlman, E. S., & Wilson, A. S. 2005, ApJ, 627, 140
Pottschmidt, K., et al. 2006, A&A, 452, 285
Poutanen, J., & Svensson, R. 1996, ApJ, 470, 249
Quataert, E. 1998, ApJ, 500, 978
Quataert, E., & Gruzinov, A. 1999, ApJ, 520, 248
Reid, M. J., et al. 1989, ApJ, 336, 112
Reimer, A., Protheroe, R. J., & Donea, A.-C. 2004, A&A, 419, 89
Reynolds, C. S., et al. 1996, MNRAS, 283, 873
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Smith, D. M., Dawson, D. M., & Swank, J. H. 2007, ApJ, 669, 1138
Smith, D. M., Heindl, W. A., Marketed, C. B., & Swank, J. H. 2001, ApJ, 554, L41
Smith, D. M., Heindl, W. A., & Swank, J. H. 2002, ApJ, 569, 362
Sparks, W. B., Biretta, J. A., & Macchetto, F. 1996, ApJ, 473, 254
Spencer, R. E., & Junor, W. 1986, Nature, 321, 753
Stiavelli, M., Peletier, R. F., & Carollo, C. M. 1997, MNRAS, 285, 181
Sun, W. H., & Malkan, M. A. 1989, ApJ, 346, 68
Sunyaev, R. A., & Titarchuk, L. G. 1980, A&A, 88, 121
———, 1985, A&A, 143, 374
Tavani, M., & Brookshaw, L. 1995, ASP Conf. Ser., 72, 139
Tonry, J. L., et al. 2001, ApJ, 546, 681
Wilson, A. S., Binette, L., & Storchi-Bergmann, T. 1997, ApJ, 482, L131

stood by an accretion disk model with a contribution from the jet in the radio range. The acceleration of electrons to a relativistic energy and the role of the relativistic electrons in producing the high energy emission from the jet may be important to study the spectra from the knots.

4. CONCLUDING REMARKS

In this Letter, we calculated the spectra from generalized two-component advective accretion disks located around stellar-mass and supermassive black holes. Specifically, we applied our method for the AGN M87, perhaps the most massive black hole candidate known. We find that only the sub-Keplerian component is enough to describe the black hole spectrum very satisfactorily. In a sub-Keplerian disk, the flow is almost freely falling and the infall timescale for M87 in the CENBOL region (∼ tens of r_g) is of the order of a few months. Not surprisingly, the observed variability of the core of M87 in optical/X-ray wavelength is reported to be of the order of a few months (Perlman et al. 2003; Harris et al. 1997), supporting our view. For a Keplerian disk the viscous timescale would be a few orders of magnitude higher. Out fit with a sub-Keplerian flow alone is excellent. What is more, since the shocks are produced in sub-Keplerian flows, the shock acceleration provides a natural explanation for the flat spectrum. The jets which are produced from the CENBOL also contribute to the radio emission. The nonthermal tail due to Comptonization of the synchrotron photons fits the Chandra data and we believe that it extends at least a few tens of MeV. At higher energies, one may have to consider the hadronic interactions, which is beyond the scope of the present Letter.

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