JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
29: S97 ~ S98, 1996

THEORETICAL CONSIDERATIONS ON THE VARIABILITY OF ACTIVE GALACTIC NUCLEI

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ABSTRACT

Variability of active galactic nuclei is now a well-known phenomenon. This remains to be fully explained by a theoretical model of the central engine. Time scales of AGN variability seem to range continuously from hours up to months. The short time scale variability must be related to the phenomena on the event horizon of the black hole, while the long one to those in the accretion disk or surrounding matter. Based on the axisymmetric, nonstationary model of the central engine, we discuss theoretical considerations on the variability of active galactic nucleus.

I. INTRODUCTION

Variability of the emission-line spectra of active galactic nuclei (hereafter, AGNs) is now a well-known phenomenon. Typical time scales of variation seem to range continuously from hours up to months. This remains to be fully explained by a theoretical model of the central engine in an AGN.

An excellent axisymmetric, stationary model has been investigated as the background of the Blandford-Znajek process (Blandford and Znajek 1977), which consists of the supermassive black hole surrounded by a magnetized accretion disk. The model was reformulated and extended by Thorne and Macdonald (1982), Macdonald and Thorne (1982), and Thorne *et al.* (1986) in '3+1'-spacetime formalism.

Based on this axisymmetric, stationary model a time-dependent model was established by Park and Vishniac (1989*a*, 1989*b*, hereafter PV*a* and PV*b*, respectively). The main point was to add the secular effects of mass accretion to the original axisymmetric, stationary model. PV*a* and PV*b* investigate the axisymmetric, nonstationary electrodynamics of a black hole and its accretion disk, respectively. This time-dependent model offers various ways of theoretical consideration in explaining the variability of AGNs.

II. THE AXISYMMETRIC, NONSTATIONARY MODEL

In this section we will summarize the basic equations of the axisymmetric, nonstationary electrodynamics of a black hole and its magnetosphere. Throughout this presentation we define our units such that $c = G \equiv 1$, and the central black hole is assumed to be a Kerr black hole which possesses the total mass M, the angular momentum J, and the angular momentum density $a(\equiv J/M)$.

Axisymmetric, nonstationary conditions can be represented as (PV*a* eq. [3.1]),

$$\mathbf{m} \cdot \nabla f = 0, \quad \mathcal{L}_{\mathbf{m}} \mathbf{f} = \mathbf{0} \qquad (2.1a)$$

and

$$\frac{\partial f}{\partial t} \equiv \dot{f} \neq 0, \quad \frac{\partial \mathbf{f}}{\partial t} \equiv \dot{\mathbf{f}} \neq \mathbf{0}, \qquad (2.1b)$$

where $\mathbf{m}$ is a Killing vector of the axisymmety, $\mathcal{L}$ means the Lie derivative, and f and $\mathbf{f}$ are any scalar and vector, respectively.

Throughout this presentation $\mathbf{m}$ has the same magnitude as $\tilde{\omega}$, the separation between the symmetric axis of the black hole and a Fiducial Observer (hereafter FIDO; see Thorne *et al.* 1986). Let ∂A be an $\mathbf{m}$-loop, A be any surface bounded by ∂A but not intersecting the event horizon of the black hole, and $d\mathbf{A}$ be the normal vector on an infinitesimal area on A. Then we can define the total electric current passing downward through A, $I(\mathbf{x}, t)$, the total magnetic flux passing upward through A, $\Psi(\mathbf{x},\mathrm{t})$, and the total electric flux passing upward through A, $\Phi(\mathbf{x},\mathrm{t})$, as (PV*a*, eq. [3.2]),

$$I(\mathbf{x}, t) \equiv -\int_A \alpha \mathbf{j} \cdot d\mathbf{A}, \qquad (2.2a)$$

$$\Psi(\mathbf{x}, t) \equiv \int_A \mathbf{B} \cdot d\mathbf{A}, \qquad (2.2b)$$

and

$$\Phi(\mathbf{x}, t) \equiv \int_A \mathbf{E} \cdot d\mathbf{A}, \qquad (2.2c)$$

where $\mathbf{j}$ is the current vector and α is the lapse function of the FIDO.

In terms of these the electromagnetic fields described by the FIDO are given by (PV*a*, eqs. [3.3], [3.5], and [3.6])

$$\mathbf{E}^T = -\frac{2}{\alpha\tilde{\omega}} \left(\frac{\dot{\Psi}}{4\pi} \right) \mathbf{e}_{\hat{\varphi}}, \qquad (2.3a)$$

$$\mathbf{E}^P = \mathbf{E} - \mathbf{E}^T, \qquad (2.3b)$$

$$\mathbf{B}^T = -\frac{2}{\alpha\tilde{\omega}} \left(I - \frac{\dot{\Phi}}{4\pi} \right) \mathbf{e}_{\hat{\varphi}}, \qquad (2.3c)$$

and

$$\mathbf{B}^P = -\frac{\mathbf{e}_{\hat{\varphi}} \times \nabla\Psi}{2\pi\tilde{\omega}}, \qquad (2.3d)$$

where T, P denote the toroidal and poloidal components respectively.

III. ANALYSIS AND DISCUSSION

A system cannot be observed to vary on a shorter time scale than the length scale l. For any changes must appear smeared out over the difference in time it takes light to reach us from the system. In general, therefore, observations of variability on a time scale τ provide an upper limit as $\tau \geq l$. This is equal to $\tau \geq M$ for an AGN because $l \sim M$ for a black hole.

(a) $\tau \sim M$ VARIABILITY

Time scales of AGN variability seem to range continuously from hours up to months. The black hole time

$$t \sim M \sim \frac{1}{\Omega^H}, \qquad (3.1)$$

where Ω^H is the angular velocity of the black hole, is in order of hours for supermassive ones and naturally matches to the shortest scale.

Therefore, the shortest variability must be related to the phenomena on the event horizon of the black hole. In PV*a* we find that the electrodynamic power output from the black hole can be variable on time scales in order of equation (3.1). The first thing that lies on the horizon and has something to do with the variability is the magnetic field. Park(1994) introduced an electrodynamic variable analysis to the power fluctuation.

Since the magnetic field lines are anchored on the accreting matter, they continuously fall on the event horizon of the central supermassive black hole and increase the net field strength of the hole magnetosphere. The field strength, however, cannot increase without an upper limit and, therefore, it will be decreased by some unknown processes. These increasing and decreasing modes enables Ψ to vary as $\dot{\Psi}/\Psi \sim i\Omega^H\tau$ and, therefore, the power P to fluctuate since $P = P(\Psi)$.

This may be repeated with period

$$\tau \sim M \sim \frac{1}{\Omega^H} \qquad (3.2)$$

due to the continuously-incoming field lines and explain the shortest time scale variability of power output, therefore, variability of AGNs. In equation (2.3*a*) we find one interesting fact that the direction of the toroidal electric field can also be varied periodically because $\dot{\Psi}$ can be positive or negative. This implies that the description of the modes will be much more complicated.

Finding the unknown processes seems to be beyond the scope of this analysis, but it is still worth discussing that such processes may be related, somehow, to the shortest variability. We may be able to estimate it rigorously if we figure out whole the mechanism. The period, however, may not be very different from Eq. (3.2).

(b) $\tau > M$ VARIABILITY

In PV*b* we find that the electrodynamic power output from the accretion disk can be variable on time scales associated with secular instabilities. The point was that the local fluctuation in fluid velocities in the accretion disk will cause fluctuations in the nonthermal component of the radiation by the Blandford-Znajek process. The time scales for these fluctuations, therefore, will reflect the range of orbital periods in the inner annulus of the disk. The associated time scale is in order of

$$\tau \sim \frac{1}{\Omega^F} > \frac{1}{\Omega^H} \sim M, \qquad (3.3)$$

where Ω^F is the angular velocity of the field lines.

The power fluctuation for $\tau > M$ must be closely related to the detailed structure of the accretion disk. Park and Vishniac(1996) consider the radial buoyancy of vertical magnetic field lines in radiation and gas pressure dominated accretion disks. We find that that the fields in disks are generated at small radii by an internal disk dynamo. This conclusion can be avoided if the external field imposes a supersonic Alfvén speed within the disk without giving rise to interchange instabilities. In any case we note that variations in the mass transfer rate will lead directly to a modulation of the nonthermal emission from the disk system. Readers are directed to Vishniac's presentation for details.

ACKNOWLEDGEMENTS

This work was supported in part by the Basic Research Project 96-5200-002-313 of Korea Astronomy Observatory.

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