NONLINEAR EXPANSION TRIGGERED BY MAGNETIC STRESS IN ACCRETION FLOW ONTO A BLACK HOLE

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Abstract. The paper is an investigation of the magnetohydrodynamics(MHD) of the quasi-radial accretion onto a rotating black hole. It is demonstrated that the nonlinear effects in the accretion flow accelerate the rate of expansion of the Alfven mode. The accretion flow becomes unstable at the weak strength of magnetic field which is about one-thirtieth of the expected value by the linear theory.

1. Introduction

The stability pf MHD accretion towards a body was investigated by Williams (1975). It was derived from a perturbation method that, if the flow is super-Alfvénic at infinity but sub-Alfvénic further in, a smooth transition at the Alfvén surface would be unstable. The results were generalized to show that any ideal aligned-field flow where gas passes smoothly from a super-Alfvénic region into a sub-Alfvénic region will be unstable, without exception. It was concluded that super-Alfvénic flow towards a body most become sub-Alfvénic via a shock, followed by turbulent flow. The above conclusion was based on the linear analysis. We investigate here the nonlinear effects of the stability of the MHD accretion with full numerical MHD code.

The magnetic field lines near a rotating black hole are twisted by a frame-dragging effect and, thus, the rotational energy of the black hole is stored in the magnetosphere around the black hole. The twisted magnetic field exerts a torque on an ambient plasma. The particles acted on by magnetic stress either increase or decrease their angular momentum. The increased kinetic energy of particles is changed in some cases to thermal energy, wave energy or radiation energy. We first consider the possible magnetohydrodynamical structure formed around a black hole in a simple case in which initially a homogeneous field is changed by infalling gas with no angular momentum at infinity.

The two types of process were proposed regarding the extraction of rotational energy from a Kerr black hole by means of magnetic fields. One is an electromagnetical extraction (Blandford and Znajek 1977) and the other is a hydromagenetical-type extraction (Ruffini an Wilson 1975). The former type magnetic field is a force-free field generated by the surrounding matter outside the event horizon. The interaction of a magnetic field with the hole's rotation produces a "battery-like" behavior of the hole's horizon (Thorne et al. 1986). The latter extraction process is caused by the fact that two shells of different radii formed outside the event horizon are dragged due to the

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rotation of the black hole with a characteristic angular velocity. If connections between the two shells are made (ropes, springs or in the case of the magnetosphere magnetic lines of forces), rotational energy can be pumped out from the innermost shell to an external one, and the rotational energy can be extracted from a black hole (Ruffini 1977). Whereas electromagnetic extraction processes have been studied by many authors, the latter case has not. When the magnetic energy builds up to equipartition with the kinetic energy of infalling gas, the extraction energy could be comparable with the observed radiation energy from active galactic nuclei (AGN). Therefore, we consider the hydromagnetical extraction process. The maximal extraction rate is determined in this process by the maximum energy flux of electromagnetic field in a stabile accretion.

2. Model of Magnetohydrodynamical Accretion onto a Rotating Black Hole

We set the initial conditions such that the magnetic field and the gas are homogeneous, and the gas observed in locally non-rotating frame (LNRF) is rest. Two types of boundary conditions are adopted at the outer boundary. One is the free fall condition in which the gas density and the magnetic field strength are given by the analytic solutions of the free fall (Yokosawa, Ishizuka and Yabuki 1991). Other is the quasi-stationary condition in which the gas density is constant and the magnetic field strength slowly increases. The latter case is calculated in order to evaluate the energy and angular momentum transport rate of a black hole to the ambient matter in a stationary state. The initial gas temperature is selected either to be cool or to be hot. In the hot case, the gas pressure behind the shock front is comparable with the magnetic pressure. The calculating space is $r = 1.07r_h \sim 10r_h$ and $\theta = 0 \sim \pi/2$, where r_h is the horizon radius. The mesh size is 125 in the r-direction and 100 in the θ-direction. Computations were performed on the workstation, MIPS RS3230.

3. Dynamics and Stability of MHD Accretion

(a) Dynamics of accretion flows bounced by the magnetic stress has been presented. The first bounce occurs at the poles in the vicinity of the horizon (figure 1). The meridian motion is remarkable in the bounced region, which is a characteristic common to all strong magnetic stress either in the case of rapidly rotating black hole or in slow rotating black hole. When the gas pressure is comparable with the magnetic stress at the bounced region, no remarkable meridian motion appears. If the gas pressure at the shock front is higher than the magnetic pressure, the shock wave becomes quasi-stationary, that is, its wave is a standing wave formed near the event horizon. When

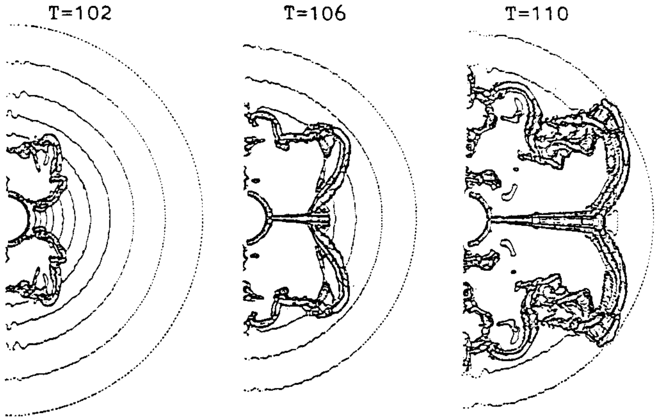

Fig. 1. The dynamical evolution of MHD accretion onto a rotating black hole. The density contours are presented by lines with the level n, $10^{n/5}$. The first instability occurs at the poles in the vicinity of the horizon.

the temperature of the falling gas is so low as the magnetic pressure predominates over the gas pressure, the magnetic energy stored at the shocked shell is released in a radially expanding wave. After a while, the expanding gas returns to falling onto the black hole with frozen magnetic field.

(b) The maximum energy density of the magnetic field obtained in quasi-stationary accretion flows is $B^2_{\mathrm{MAX}} \approx 10^{-3}\rho c^2$. The more strong magnetic field produces the shock structure in the flow. The rotational velocity of the fluid reaches to $v_{\phi,\mathrm{MAX}} \approx 0.1c$. The stored energy in the magnetosphere around a black hole is about 0.1 percent of the rest mass energy of the accreting matter.

(c) The linear theory on the stability of trans-Alfvenic flow showed that magnetized accretion flow becomes unstable at the Alfvenic surface, i.e. $M_A = 1$. The numerical simulation shows that the quasi-pulsation is triggered by the magnetic stress at the Alfven Mach number $M_A \approx 30$.

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