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Magnetic Activities of Black Hole Accretion Disks

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Magnetic fields drive various activities in differentially rotating disks (accretion disks) formed around a gravitating object. In such disks, magnetic fields are amplified by the magneto-rotational instability (MRI [1]). Three-dimensional global magnetohydrodynamic (MHD) simulations (e.g., [2]) have shown that the amplification of magnetic fields in non-radiative disks saturates when plasma β is around 10. Magnetic turbulence generated by MRI enables accretion of the disk material by transporting angular momentum outward through Maxwell stress. The average ratio of the Maxwell stress to gas pressure is 0.01-0.1. This corresponds to the α-viscosity assumed in theories of accretion disks.

In accretion disks, vertical stratification of the disk due to the gravity of the central object plays essential roles in transporting the magnetic flux from the disk to the disk corona. The buoyant escape of magnetic flux by Parker instability limits the strength of magnetic fields sustained in the disk [2]. Buoyantly rising magnetic loops anchored to the disk are twisted by differential rotation, inflate, reconnect, and form large-scale open magnetic fields threading the disk. Magnetically driven winds/jets emanate from the disk along the magnetic fields. Radio jets observed in nearby radio galaxies such as M87 can be explained by magnetically driven jets from radiatively inefficient accretion flows (RIAF) around a super-massive black hole. The existence of the black hole in M87 has been confirmed by the observation of the black hole shadow by EHT (Event Horizon Telescope)[3].

Numerical results indicate that mean azimuthal magnetic fields in differentially rotating disks reverse quasi-periodically with time scale about 10 rotation period of the disk. Mean azimuthal magnetic fields can either be symmetric or anti-symmetric with respect to the equatorial plane of the disk [4]. Since the polarity of the buoyantly rising magnetic loops changes with the dynamo cycle, the direction of the large-scale poloidal magnetic fields threading the disk reverses quasi-periodically. The field reversal triggers magnetic reconnection and drives intermittent ejection of jets by release of the magnetic energy. Furthermore, the field reversal prevents the accumulation of poloidal magnetic flux near the black hole, and affects the efficiency of the extraction of the rotational energy of the black hole.

X-ray time variabilities of black hole candidates have been monitored over 40 years. Some black hole candidates show recurrent outbursts. During the outburst, they show transitions between a hard state dominated by hard X-rays and a soft state dominated by soft X-ray emissions. The hard-to-soft transition begins when the accretion rate exceeds 1% of the Eddington accretion rate corresponding to the Eddington luminosity defined as the luminosity when the radiative force exceeds gravity in spherically symmetric accretion flows.

Three-dimensional global radiative MHD simulations of black hole accretion flows showed that when the accretion rate exceeds 1% of the Eddington accretion rate, magnetic pressure supported (low β) disk is formed outside the optically thin hot accretion flow (RIAF) near the black hole because the azimuthal magnetic field is enhanced by vertical contraction of the disk due to radiative cooling [5]. The left panel in figure 1 shows the density distribution obtained by three-dimensional MHD simulations of RIAF, and the right panel shows the density distribution during the hard-to-soft transition obtained by three-dimensional radiation MHD simulation (Igarashi et al. 2019 in preparation). When the accretion rate is around 10% of the Eddington accretion rate, RIAF near the black co-exists with the outer optically thick, cool disk. Numerical results can explain the luminous hard X-ray emission, sporadic ejection of jets, and quasi-periodic oscillations (QPOs) observed during the hard-to-soft transition.

References

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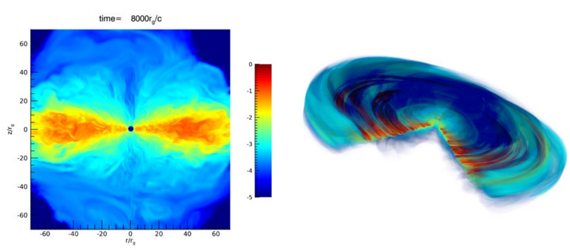

Figure 1 (Left) Density distribution of radiatively inefficient accretion flow. (Right) 3D density distribution during the hard-to-soft state transition.