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ORIGINAL ARTICLE

Magnetic-Tower Jet Solution for Launching Astrophysical Jets

The formation of the first jets in the universe

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Abstract In spite of the large number of global three-dimensional (3-D) magnetohydrodynamic (MHD) simulations of accretion disks and astrophysical jets, which have been developed since 2000, the launching mechanisms of jets is somewhat controversial. Previous studies of jets have concentrated on the effect of the large-scale magnetic fields permeating accretion disks. However, the existence of such global magnetic fields is not evident in various astrophysical objects, and their origin is not well understood. Thus, we study the effect of small-scale magnetic fields confined within the accretion disk. We review our recent findings on the formation of jets in dynamo-active accretion disks by using 3-D MHD simulations. In our simulations, we found the emergence of accumulated azimuthal magnetic fields from the inner region of the disk (the so-called magnetic tower) and also the formation of a jet accelerated by the magnetic pressure of the tower. Our results indicate that the magnetic tower jet is one of the most promising mechanisms for launching jets from the magnetized accretion disk in various astrophysical objects. We will discuss the formation of cosmic jets in the context of the magnetic tower model.

Keywords Accretion · Accretion disks · Black hole physics · ISM: jets and outflows · MHD · Relativity

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1. Introduction

Jets in active galactic nuclei (AGNs) are one of the most largest single objects in the universe, and also they are ubiquitous in different systems such as X-ray binaries (XRBs) and young stellar objects (YSOs). The comprehensive understanding of astrophysical jets is that they are driven by the gravitational energy of material accreting towards central objects, such as stars and compact objects. In fact, many observations suggest that astrophysical jets are associated with disks/tori, that may feed inner accretion disks. Therefore, the launching mechanism of jets strongly depends on the underlying accretion flows. In this review, we mainly focus on the development of a theory of accretion disks and jets after the early 1990s. In the followings, we first remark on magnetohydrodynamical (MHD) studies of accretion flows and outflows. We then move on to studies of jets from accretion disks using global MHD simulations. In Section 2, we introduce our recent discovery of the formation of magnetic tower jets in dynamo-active accretion disks. Finally, in Section 3, we summarize the study of magnetic tower jets.

Although an alpha-viscosity prescription provides an convenient tool for representing a steady structure of the accretion flows, the magnitude of viscosity is not a free parameter and may not be a constant in space and time. Since magnetic fields provide a source of disk viscosity, as a consequence of magneto-rotational instability (MRI; Balbus and Hawley, 1991), we expect that magnetic fields play crucial roles in the dynamics of accretion flows (see Stone and Pringle, 2001). That is, the magnetohydrodynamical (MHD) approach is indispensable. The first global 3-D MHD simulations of non-radiative accretion flows were performed by Matsumoto (1999). He calculated the evolution of magnetic fields and structural changes of a torus which is initially threaded by toroidal magnetic fields. Hawley (2000), on the other hand, calculated the evolution of a magnetized torus which confines poloidal magnetic fields. After 2000, many global 3-D MHD disk simulations starting with locally confined fields were published (e.g., Machida et al., 2000; Hawley and Krolik, 2001; Hawley, 2001; Hawley et al., 2001). All of these global simulations revealed that MRI maintains turbulent flows in the magnetized accretion disk and provides spontaneous generation of subthermal magnetic fields, however, the connection between the disks and the outflows was not resolved by these simulations (see Balbus, 2003 for a review).

The acceleration mechanism of the MHD jet has been studied extensively by many groups. Blandford and Payne (1982), for the first time, suggested a disk wind driven by interaction between disks and magnetic fields permeating the disk as the origin of the jets (see also Pudritz and Norman, 1983, 1986; Lovelace et al., 1987). They assumed that the poloidal magnetic field is much stronger than the toroidal magnetic field in the surface layer of the disk or in the disk corona, where plasma-β is low, and jets are accelerated by a magneto-centrifugal force along the magnetic field line. In this case, the plasma corotates with the magnetic field lines until the Alfvén point, beyond which toroidal fields start to dominate and hence collimation begins via the magnetic pinch effect. The pioneering simulations of MHD jets from accretion disks were performed by Uchida and Shibata (1985; see also Shibata and Uchida, 1986). They calculated the evolution of a disk threaded with vertical fields extending to infinity and found the propagation of a torsional Alfvén wave along the magnetic field lines, where the jet was accelerated by a twisted magnetic field (see also Shibata and Uchida, 1985; Meier et al., 2001: they named this process the "sweeping magnetic twist mechanism"). Accordingly, they proposed another kind of magnetically driven jet, in which the toroidal magnetic field is dominant everywhere (see also Shibata et al., 1990; Fukue, 1990; Fukue et al., 1991; Contopoulos, 1995; Kudoh and Shibata, 1995, 1997), where the jets are accelerated by the magnetic pressure. If this is the case, the Alfvén point is embedded in the disk or there is no Alfvén point, and the Blandford-Payne mechanism cannot be applied to such jets. Later, many 2-D MHD simulations of jets driven by large-scale magnetic fields permeating disks were performed (e.g., Matsumoto et al., 1996; Kudoh et al., 1998; Casse and Keppens, 2002, 2004). On the contrary to toroidal field dominated jets, in these simulations, the Alfvén point is far from the disk surface indicating that the jet is primarily accelerated by the magneto-centrifugal force (see Kudoh et al., 1998). It has alos been argued that such toroidal field dominated jets are very unstable to kink instabilities in real three-dimensional space and cannot exist in actual situations (e.g., Spruit et al., 1997). In order to study the structure and the stability of outflows driven by large-scale magnetic fields beyond the Alfvén point, some groups carried out MHD simulations of outflows from disks treated as boundary conditions (e.g., in 2-D: Todo et al., 1992; Ustyugova et al., 1995; Ouyed and Pudritz, 1997a,b, 1999; in 3-D: Ouyed et al., 2003; Ouyed, 2003). In relation to MHD disk simulations, these simulations were more concerned with the jet structure driven by vertical magnetic fields, where the disk only plays a passive role. Since angular momentum can be efficiently extracted from the surface of the accretion disks by the vertical fields, a surface avalanche produces anomalous mass accretion in those simulations. Thus, we need to be careful as to whether or not the launching mechanism of a jet depends on magnetic fields, which are provided externally or generated internally. This is the first stage in the research of astrophysical jets.

Previous studies of jets concentrated on the effects of large-scale magnetic fields permeating accretion disks. One may ask what the origin of such a large scale field is? Unfortunately, the origin of such a magnetic field is poorly understood (see Kronberg, 1994 and references therein). In addition, large-scale jet models predict that the direction of the jets are expected to be aligned with that of the large-scale magnetic field lines. Recent observations, however, show that the direction of large-scale magnetic fields are not correlated with the direction of the jets in young stellar objects (Ménard and Duchêne, 2004). Rather, we expect that the magnetic fields generated by the disk *itself* are the most promising sources of magnetic fields that drive outflows. In order to study the outflows from the magnetized disk, some groups carried out 2-D MHD simulations of outflows from dynamo-active disks treated as boundary conditions (e.g., Turner et al., 1999; von Rekowski et al., 2003). On the other hand, Kudoh et al. (2002) carried out 2-D axisymmetric MHD simulations of a thick torus involving poloidal magnetic fields and found a rising magnetic loop, which behaves like a jet, from the torus. This is the second stage in the research of astrophysical jets.

Recently, outflows have also appeared in 3-D MHD simulations of accretion disks. Hawley and Balbus (2002; hereafter HB02) calculated the evolution of a torus with initial poloidal fields and found three well-defined dynamical components: a hot, thick, rotationally supported, high-β Keplerian disk; a surrounding hot, unconfined, low-β coronal envelope; and a magnetically confined unbound high-β jet along the centrifugal funnel wall (see also Igumenshchev et al., 2003) These studies are a key to developing the next stage of magnetic jet models; what we call a magnetic tower jet. Now, we have entered the third stage in the research of jets in magnetized accretion flows.

2. Magnetic tower jets

Lynden-Bell and Boily (1994: hereafter LB94) studied the evolution of force-free magnetic loops anchored to the star and the disk. They obtained self-similar solutions for the evolution of magnetic loops. They found that the loop is unstable against twist injection from rotating disks and that the loop expands along a direction of 60 degrees from the rotation axis of the disk (see also Uzdensky et al., 2002a,b; Uzdensky, 2002). Lovelace et al. (1995) pointed out that the dipole magnetic field of the star deforms itself into an open magnetic field due to the differential rotation between the star and the disk. Hayashi et al. (1996: hereafter HSM96) carried out, for the first time, MHD simulations of the magnetic interaction between a protostar and its surrounding accretion disk. They discovered an outflow driven by expanding magnetic loops and a magnetic flare as a result of magnetic reconnection in the loop. Later, Goodson et al. (1997) carried out similar simulations and found the density collimation along the rotation axis of the disk, which looks like a jet. (see also Goodson et al., 1999; Goodson and Winglee, 1999; Fendt and Elstner, 1999; Keppens and Goedbloed, 2000; Matt et al., 2002). Although they found the expanding magnetic loops, such magnetic loops are not collimated. Subsequently, magnetostatic configuration of collimated magnetic loops (a so-called as magnetic tower) anchored between the star and the disk were studied by Lynden-Bell (1996, 2003: hereafter L96, L03, respectively). He showed a solution of a magnetic tower surrounding by external plasma with finite pressure (see also Li et al., 2001). However, the formation and the evolution of such a magnetic tower have not been resolved until 2004. In the followings, we review the published simulations of magnetic tower jets.

2.1. Formation of a magnetic tower in the magnetosphere of a neutron star

Kato et al. (2004a: hereafter KHM04) extended HSM96 and studied the magnetic interaction between a neutron star and a disk by using 2-D axisymmetric MHD simulations. Initial models of their study are illustrated in Fig. 1a. They assume a rotating torus surrounding a weakly magnetized neutron star with a dipole magnetic field. Outside the torus, they assume an isothermal, hot, low-density hydrostatic corona. They found an expansion of the magnetic loops as a result of the twist injection from the disk, due to the differential rotation of the disk and the star. The magnetic loop ceases to splay out when the magnetic pressure balances with the ambient gas pressure. Afterwards, the expanding magnetic loop forms a cylindrical tower of helical magnetic fields whose height increases with time (Fig. 2a). A key discrimination from previous simulations is the ambient corona. In previous MHD simulations of disk-star magnetic interactions, the magnetic tower structure was not so prominent, because the ambient gas pressure was too low to confine the magnetic tower inside the computational box. It is interesting to note that expanding magnetic loops can also be collimated by large-scale vertical magnetic fields, if they are associated with accretion disks (see Matt et al., 2003). Lastly, KHM04 discovered, for the first time, the formation and evolution of a magnetic tower, which is consistent with that proposed in L96. Independently, Romanova et al. (2004) also found the formation of a magnetic tower in a magnetosphere of a protostar in the propeller regime (see also Romanova et al., 2005).

2.2. Formation of a magnetic tower in a black hole accretion flow

Kato et al. (2004b; hereafter KMS04) studied the structure of non-radiative MHD flows starting with a rotating torus with initially poloidal localized fields around a non-spinning black hole by using the pseudo-Newtonian potential (Paczyński and Wiita, 1980). Initial models of their study are

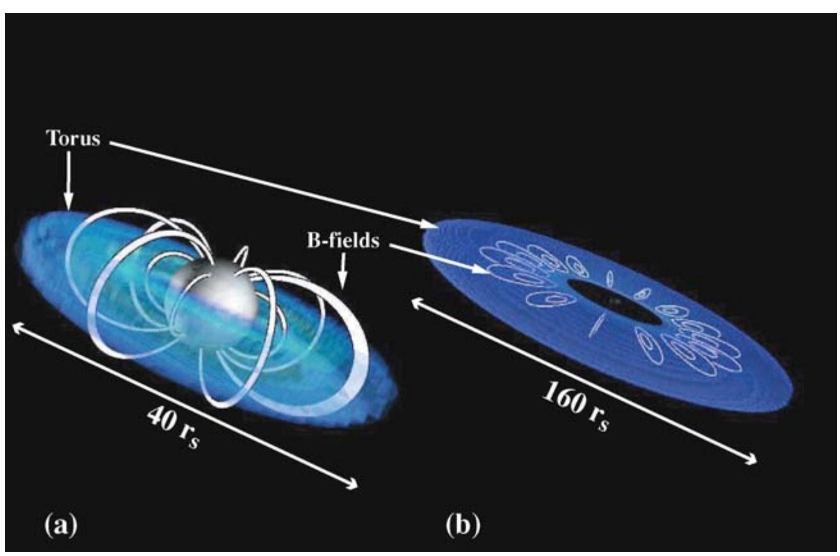

Fig. 1 Initial models of our simulations: (a) A rotating torus (*light-blue region*) is surrounded by a weakly magnetized neutron star (metallic-gray region). Solid lines indicate a dipole magnetic field threading the torus. (b) A rotating torus (*light-blue region*) is surrounded by a non-rotating black hole. *Solid lines* indicate subthermal poloidal magnetic fields confined within the torus

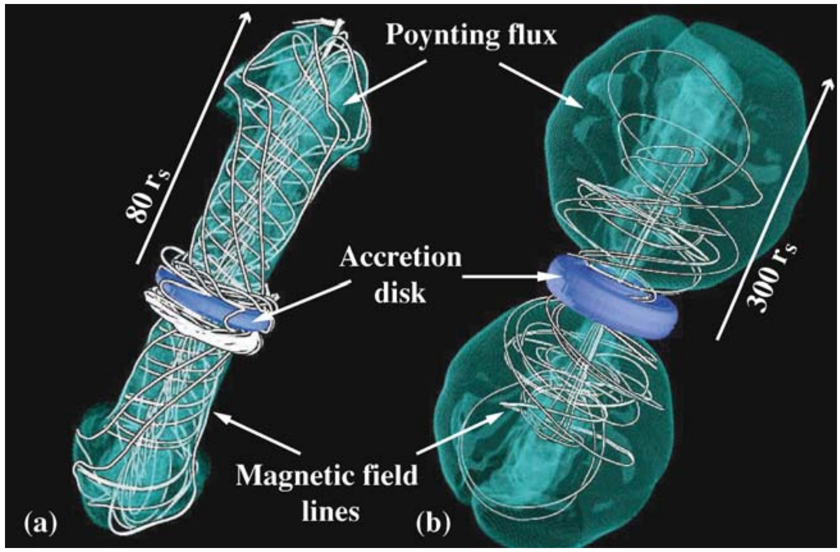

Fig. 2 Snapshots of our simulations: (a) Formation of a magnetic tower jet in the magnetosphere of a neutron star. (b) Formation of a magnetic tower jet in the magnetized accretion disk around a black hole. In both figures, the blue region, light-blue region, and solid lines indicate the isovolume of the density of the accretion disk, the isovolume of the Poynting flux, and magnetic field lines, respectively. To see animations of our simulations, the interested reader is directed to the link at `http://www.ccs.tsukuba.ac.jp/people/ykato/researches/`

illustrated in Fig. 1b. They found the emergence of a magnetic tower from the magnetized accretion flows, when the bulk of the torus material reaches the innermost region close to the central black hole (Fig. 2b). The fields are mostly toroidal in the rim regions of the jets, whereas poloidal (vertical) fields dominate in the inner core of the jet. The collimation width of the magnetic tower depends on the coronal pressure; the more enhanced the coronal pressure is, the more collimated the jet is. Non-negligible coronal pressure tends to suppress the emergence of MHD jets. In contrast to magnetic towers in the magnetoshere of neutron stars, which are generated by winding-up a dipole magnetic field, the magnetic tower in black hole accretion flows is generated by inflating toroidal magnetic fields accumulated inside the accretion disk. Our 3-D magnetic tower solution in black hole accretion flows is basically the same as LB96 proposed. A magnetic tower jet in KMS04 is consistent with the toroidal field dominated jet, since the magnetic tower is made of a toroidal field generated by dynamo action within the disk. KMS04 showed, for the first time, that such toroidal field dominated jets survive at least for a few orbital periods of the initial torus. The most striking feature of a magnetic tower jet in KMS04 is the natural emergence of magnetic fields from the disk, that can accelerate the jets, and hence a magnetic tower jet is a promising model for launching astrophysical jets from accretion disks in various astrophysical objects.

Independently, De Villiers et al. (2003) carried out 3-D general relativistic MHD simulations of the magnetized accretion flows plunging into the spinning black hole and found the formation of magnetically dominated evacuated region near the poles where outflows exist (they called it a funnel: see also McKinney and Gammie, 2004; Hirose et al., 2004). In contrast to HB02, the funnel is magnetically dominated, indicating that the funnel is the main product of the emergence of a magnetic tower from the disk (see also De Villiers et al., 2005; Hawley and Krolik, 2006).

3. Conclusion

In these proceedings, we have briefly reviewed the MHD study of accretion flows and jets and have discussed recent progress in the study of magnetic tower jets. We should remark on the definition of a magnetic tower jet, because the formation process of magnetic towers is different in the magnetosphere of a star as compared to that in a dynamo-active accretion flow. A magnetic tower is generated by a twisted magnetic loop, supported by an external force, anchored between differential rotation mediums (see L03), however, many MHD simulations of magnetized accretion flows indicate that a magnetic tower can also be produced via the emergence of toroidal magnetic fields generated inside a dynamo-active accretion disk. In other words, magnetic tower jets can extend more than the scale of pre-existing magnetic fields that drive the jet. Thus, jets that are accelerated by small-scale magnetic fields may be appropriate for the definition of magnetic tower jets. Magnetic tower jets could well be the first jets formed in the early universe, because the large-scale structure of strong magnetic fields are yet to develop in the star forming regions and galaxies at high redshift. Finally, we expect that magnetic tower jets will give a standard framework for the next stage in the research of launching jets.

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