Gravitational-Wave Radiation from Magnetized Accretion Disks
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The detectability of gravitational wave (GW) radiation from accretion disks is discussed based on various astrophysical contexts. In order to emit GW radiation, the disk shape should lose axial symmetry. We point out that a significant deformation is plausible in non-radiative hot accretion disks because of enhanced magnetic activity, whereas it is unlikely for standard-type cool disks. We have analyzed the 3D magnetohydrodynamical (MHD) simulation data of magnetized accretion flow, finding non-axisymmetric density patterns. The corresponding ellipticity is $\epsilon \sim 0.01$. The expected time variations of GW radiation are overall chaotic, but there is a hint of quasi-periodicity. GW radiation has no interesting consequence, however, in the case of close binaries, because of very tiny disk masses. GW radiation is not significant, either, for AGN because of very slow rotation velocities. The most promising case can be found in gamma-ray bursts or supernovae, in which a massive torus (or disk) with a solar mass or so may be formed around a stellar-mass compact object as the result of a merger of compact objects, or by the fallback of exploded material towards the center in a supernova. Although much more intense GW radiation is expected before the formation of the torus, the detection of GW radiation in the subsequent accretion phase is of great importance, since it will provide a good probe to investigating their central engines.

Introduction

Gravitational wave (GW) radiation is expected to be detected within 10 years or so, thereby opening a new window to probe extremely high-density objects and the early universe (see, e.g. Thorne 1987, 1997; Blair 1991; Tsubono et al. 1997). When detected, the impact will be enormous and the understanding of astrophysical objects should inevitably undergo revolutionary development. It is thus of great importance to discuss at this moment what kinds of objects can emit GW radiation. In the present study, we consider if it is feasible to detect GW radiation from accretion disks in general contexts.

At first glance, it is unreasonable to expect GW radiation from accretion disks, since, while the generation of GW requires the presence of quadruple moment, the usual disk models are constructed under the assumption of axisymmetry. Actually, the axisymmetric assumption is thought to be quite generally satisfied (see, e.g., Kato et al. 1998 for a review of various disk models). Then, how and under what circumstances can non-axisymmetry arise?

A non-axisymmetric disk structure is often discussed in the context of accretion disks in close binary systems. Since the shape of the Roche lobe is not totally spherically symmetric, we expect a disk there to lose axial symmetry, especially when the disk size is large, close to the size of the Roche lobe (Paczyński 1977). Another good indication of non-axisymmetric structure is frequently discussed based on hydrodynamical simulations; e.g. Sawada et al. (1986). Note that the presence of spiral patterns on a disk was discovered through the observing technique of Doppler tomography (Steeghs et al. 1997). As we will see later, however, because disks in close binary systems have tiny mass, the production of strong GW radiation is unlikely.

Alternatively, strong magnetic fields, if they ever exist, could greatly modify the disk structure. This is the subject of the present study. As was first discussed by Shakura and Sunyaev (1973) and later demonstrated by many authors through MHD simulations (Matsumoto 1999; Stone et al. 1999; Machida et al. 2000; Hawley et al. 2001), the magnetic energy can be amplified by the number of MHD instabilities together with differential rotation up to the value of $p_{\text{mag}}/p_{\text{gas}} \sim 0.01$–1 (e.g. Machida et al. 2000). The corresponding viscosity parameter is $\alpha \sim 0.01 – 0.1$. This is just in the range that we require to account for the observations of dwarf-nova outbursts (Cannizzo 1993) and X-ray nova eruptions (Mineshige, Wheeler 1989).

In standard-type disks, however, it is hard to believe a large influence of magnetic fields on the shape of the disk, since the magnetic energy is, at most, comparable to the internal energy of the gas, which is much less than the kinetic (rotational) energy of the gas as a consequence of efficient radiative cooling of the disk material. In other words, the magnetic pressure cannot overcome the gravitational force in such radiation-dominated accretion flow. In advection-dominated regimes (see Kato et al. 1998 for a review), in
contrast, the internal energy of gas can be comparable to its kinetic energy and potential energy because of a low radiation efficiency. We can then expect a large influence of magnetic fields on the dynamics of accretion disks.

Another argument to support this idea comes from the observed complex variability commonly observed in many black-hole candidates during their hard state. In that state, the spectra are hard, and a hot accretion flow model (ADAF model) can fit the observations (Ichimaru 1977; Narayan et al. 1996). Although its origin is not yet established, many authors suggest that the variability could be caused by a sporadic release of magnetic energy triggered by magnetic reconnection and flares (Takahara 1979; Galeev et al. 1979). Without large magnetic field energy, it is difficult to account for substantial variations. This idea is consistent with the absence of large fluctuations during the soft state, when a standard-type disk seems to be present. It then follows that a non-axisymmetric disk structure may be generated by magnetic fields in cooling-inefficient regimes (i.e. adiabatic regimes) of disk accretion. In fact, the global MHD simulation of a disk exhibits a spatial inhomogeneous structure (Kawaguchi et al. 2000). Finally, note that large fluctuations are also observed in the high-luminosity state. Magnetic activities also seem to be enhanced in such a state (e.g. Mineshige et al. 2000).

We, here, consider GW radiation from accretion disks, the shapes of which are possibly influenced by large magnetic fields or other effects. In section 2 we calculate the moments of inertia by using the MHD simulations data and see to what extent a deviation from an axisymmetric disk can be expected. We then discuss the detectability of GW radiation in various astrophysical contexts. The final section is devoted to discussion.

Inhomogeneous Density Structure Created by Magnetic Fields Here, we analyze 3D MHD simulation data newly calculated by Machida and Matsumoto (2002). They started the simulation with a torus (Okada et al. 1989) threaded by weak toroidal fields (see Machida et al. 2000) in a pseudo-Newtonian potential (see similar calculations by Hawley, Krolik 2001). The size of the calculation box was taken to be 100 $r_g$ (with $r_g$ being the Schwarzschild radius) and the mass within the last stable circular orbit at 3 $r_g$ was removed as an inner boundary condition. We have confirmed that magnetic fields are amplified up to the value of $p_{\text{mag}}/p_{\text{gas}} \sim 0.1$ within $\sim 50$ rotation periods at the reference radius of $r_0 = 50 \, r_g$ (see Machida, Matsumoto 2002 for more details).

figure[t] Fig1.eps Snapshot of the density contours of a magnetized disk on the equatorial plane [at a calculation time of $t = 32070(r_g/c)$, see Machida, Matsumoto 2002]. This figure covers the region of 20 $r_g \times 20 \, r_g$. The spacing between each contour is $\Delta \log \rho = 0.05$. frac