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The Structure of a Quasi-Keplerian Accretion Disk around Magnetized Stars

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Abstract

In this paper, we present the complete structure of a quasi-Keplerian thin accretion disk with an internal dynamo around a magnetized neutron star. We assume a full quasi-Keplerian disk with the azimuthal velocity deviating from the Keplerian fashion by a factor of ξ $(0 < \xi < 2)$. In our approach, we vertically integrate the radial component of the momentum equation to obtain the radial pressure gradient equation for a thin quasi-Keplerian accretion disk. Our results show that, at large radial distance, the accretion disk behaves in a Keplerian fashion. However, close to the neutron star, pressure gradient force (PGF) largely modifies the disk structure, resulting into sudden dynamical changes in the accretion disk. The corotation radius is shifted inward (outward) for $\xi > 1$ (for $\xi < 1$), and the position of the inner edge with respect to the new corotation radius is also relocated accordingly, as compared to the Keplerian model. The resulting PGF torque couples with viscous torque (when $\xi < 1$) to provide a spin-down torque and a spin-up torque (when $\xi > 1$) while in the advective state. Therefore, neglecting the PGF, as has been the case in previous models, is a glaring omission. Our result has the potential to explain the observable dynamic consequences of accretion disks around magnetized neutron stars.

Key words: accretion, accretion disks – dynamo – stars: neutron – X-rays: binaries

1. Introduction

It is widely agreed that the most successful theoretical model of disk accretion is that of Shakura & Sunyaev (1973). The most crucial result of their model for a disk around a black hole sets the condition for an accretion disk to be thin, i.e., the vertical scale height (H) should be much less than its radial (R) length scale. Thus, the radial component of the pressure gradient is small relative to the stellar radial gravity, and the angular velocity is Keplerian. They also found viscosity to be the main mechanism for angular momentum transfer. On the other hand, angular momentum removal can be magnetic in origin (Ghosh & Lamb 1978).

Accretion disks around magnetized stars greatly influence the stellar magnetic field, which can result in outward angular momentum transfer. Ghosh & Lamb (1979a) presented a detailed model describing the interaction of disk and stellar magnetic field. They pointed out that turbulent motion, reconnection and Kelvin–Helmholtz instability allow the stellar magnetic field to penetrate the disk and regulate the spin of the star (Ghosh & Lamb 1979b). In fact, Ghosh & Lamb (1979a, 1979b) diskovered that the star is spun down beyond the corotation radius, and vice versa. This is due to the impact of a slowly rotating outer part of the accretion disk.

The presence of an intrinsic magnetic field in the accretion disk can enhance the torque acting between an accretion disk and an accreting star (Torkelsson 1998). Tessema & Torkelsson (2010) found a complete solution of a disk structure when the dynamo is included. Their results show that the magnetic field that is produced by the dynamo leads to a significant enhancement of the magnetic torque between the neutron star and the accretion disk, compared to the model by (Ghosh & Lamb 1979a, 1979b). However, they excluded the effect of pressure gradient force (PGF).

Inclusion of the PGF would require a slight deviation from Keplerian motion (Narayan & Yi 1995). This transition results from the internal pressure $(\sim r c_s^2)$ becoming a significant fraction of the orbital energy. The disk temperatures will be elevated above the values of an unperturbed disk (Campbell & Heptinstall 1998). Thus, a hot, optically thin accretion disk cannot continuously be geometrically thin. In this case, the vertical height $H \sim c_s/\Omega_k$ (Ω_k is the Keplerian angular velocity), implying that H/R „ 1 as opposed to $H/R = 1$. This is a unique feature of quasi-Keplerian rotation, in that, when the Keplerian radial distances are shifted, the quasi-Keplerian corotation radius and the position of the disk inner edge are shifted inward (Yi et al. 1997).

Consequently, the quasi-Keplerian model may have observable and theoretical interesting results. Hoshi & Shibazaki (1977) considered a quasi-Keplerian model, but they never found a complete accretion disk structure. Later, Yi et al. (1997), who assumed the deviation from Keplerian fashion to be 0.2, diskovered that changes in magnetic torques are marked by a visible change of spin-up or spin-down torque between the disk and neutron star.

In this paper, we seek to find the complete structure of a quasi-Keplerian, dynamo-powered accretion disk around a magnetized slowly rotating neutron star. This model follows the assumptions of Shakura & Sunyaev (1973), i.e., vertical hydrostatic equilibrium, steady state, and the α-parameter for viscosity. Taking up the magnetized compact object model of Wang (1987, 1995), we then modify the Hoshi & Shibazaki (1977) model, using the formulation of Tessema & Torkelsson (2010) while taking into account the effect of radial pressure gradients. We subject our results to the observed data in order to explain such observational scenarios as those in 4U 1728-247 and 4U 1626-67 (Camero-Arranz et al. 2010).

The rest of this paper is structured as follows: Section 2 presents our basic formulation; results (both theoretical and