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A New Physical Mechanism to Account for the "Anomalous Viscosity" in Accretion Disks

X. Zhang

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Abstract. A new physical mechanism responsible for producing significant radial mass accretion in the inner disk of spiral galaxies has recently been found (Zhang 1996, ApJ, 457, 125). Since this mechanism depends only on the skewness of the global patterns (one-armed or two-armed spiral patterns, as well as skewed central bars) in the underlying disks, and since this process is collective in nature and produces an effective viscosity many orders of magnitude larger than that due to the microscopic processes, it is likely to be an important candidate for the long sought-after "anomalous viscosity" in many types of astrophysical accretion disks which admit nonaxisymmetric instabilities.

1. Introduction

One important unsolved problem in the study of accretion disks is the identification of an efficient viscous mechanism, which allows the angular momentum of the disk material to be transported outward, and thereby allows the disk material itself to accrete inward.

We present here a new candidate mechanism for anomalous viscosity, which is essentially gravitational in nature and does not require the presence of magnetic fields or convective turbulence.

2. A Collective Dissipation Process Induced by a Galactic Spiral Structure

This candidate mechanism was first investigated in the case of spiral galaxies (Zhang 1996). It was found that due to the long range nature of the gravitational interaction, a self-consistent spiral mode generally has a phase shift between the potential and density spiral patterns. This leads to a dissipative energy and angular momentum exchange between the disk matter and the spiral density wave, which is achieved locally through a collisionless shock at the spiral wave crest, owing to the instability condition there. For a unit width annular ring at radius R, we have

$$\mathcal{T}(R) = -R \int_0^{2\pi} \Sigma_1(R, \phi) \frac{\partial V_1(R, \phi)}{\partial \phi} d\phi$$

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$$= 2\pi R \frac{dL}{dt}(R) = -\pi F^2 v_c^2 \tan i \sin(m\phi_0)\Sigma_0, \tag{1}$$

where $\mathcal{T}$ is the torque applied by the spiral potential wave on the disk material; L is the angular momentum density of the disk matter; Σ_0 is the surface density and v_c is the circular velocity; Σ_1 is the spiral density amplitude; V_1 is the potential amplitude, and ϕ_0 is the phase shift; finally, F is the fractional amplitude, m the number of spiral arms, and i the pitch angle of the spiral.

3. Effective Viscosity due to a Global Nonaxisymmetric Instability

The torque expression (1) is equal to the radial derivative of the torque coupling $G(R)$ between the inner and outer disk at radius R. By comparing (1) with $\partial G/\partial R$ for a standard accretion disk, and assuming the disk has a flat rotation curve and 1/R surface density distribution, we obtain for effective viscosity

$$\nu_{eff} = \frac{1}{2} F^2 v_c \sin(m\phi_0) \tan i R, \tag{2}$$

where we have used the subscript to emphasize that the effective viscosity due to the global pattern is different in nature as that due to local shear. In particular, the energy deposition due to a global spiral pattern is in general different from that due to shearing viscosity.

For spiral modes which is capable of spontaneous growth, G must be (and is indeed found to be) of a bell shape, with the top of the bell at the corotation radius. This gives a $\frac{\partial G}{\partial R} > 0$ (or a phase shift $\phi_0 > 0$, which means potential lags density) inside corotation, and $\frac{\partial G}{\partial R} < 0$ outside corotation. This shape of the $G(R)$ curve results in angular momentum to be removed from the disk matter inside $R_{corotation}$, carried outward by the spiral density wave, and eventually deposited at the outer disk. This process results in the spontaneous growth of the spiral modes in the linear regime, and also results in the evolution of the basic state of the disk in the fully nonlinear regime (quasi-steady state of the wave mode)[1].

Since ϕ_0 changes sign at $R_{corotation}$, the effective viscosity due to a quasi-stationary spiral mode is positive inside corotation, and negative outside corotation. This is consistent with the fact that the disk matter accretes inside corotation, and excretes outside corotation.

Comparing to the standard α prescription for viscous accretion disks, we obtain (denoting by v_r the velocity dispersion)

$$\alpha = \frac{\frac{1}{2} F^2 v_c^2 \sin(m\phi_0) \tan i}{v_r^2}. \tag{3}$$

For a spiral mode of 20% amplitude, for $v_c = 220 km/s$, $v_r = 30 km/s$, $i = 20^o$, and $\phi_0 = 4^o$, we obtain $\alpha = 0.05$. If instead we have $F = 10\%$, then $\alpha = 0.01$. These values of α are within the range usually considered for accretion disks of stellar or galactic types.

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[1]Note that in order for the basic state of the disk to evolve, including radial mass accretion in the inner disk, it is not enough to have outward angular momentum *transport* by the spiral density wave. There must also be angular momentum *deposit*.

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