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THE MAGNETOVISCOUS-THERMAL INSTABILITY IN DILUTE MAGNETIZED ASTROPHYSICAL PLASMAS

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Abstract. The accretion of a very dilute plasma is thought to be the underlying cause of anomalously low accretion luminosity onto massive black holes such as Sagittarius A^*. In these plasmas, the ion collisional mean free path exceeds the ion Larmor radius, and the flows are destabilized when either the temperature or the angular velocity decreases outwards. The cause of this behavior is anisotropic thermal conduction and viscosity, both of which limit transport to follow magnetic field lines. These plasmas are of course also prone to the standard magnetorotational instability. We discuss the detailed physical conditions under which these magnetothermal and magnetoviscous instabilities arise.

1 Background

It has been shown that a magnetized fluid is linearly unstable (Balbus and Hawley 1991; Chandrasekhar 1960). This has been shown to be important for accretion because this instability, the magnetorotational instability (MRI), can efficiently transport angular momentum outwards (Balbus and Hawley 1998). In hot, dilute accretion flows such as those around black holes, the particle collisional mean free path may be comparable to or larger than the system scale. If even a weak magnetic field is present, large thermal conductivities and viscosities direct heat and momentum flux along magnetic field lines. Previous research has demonstrated that viscous and thermal diffusive transport along magnetic field lines can destabilize plasma with differential rotation (Balbus 2004b; Islam and Balbus 2005) or temperature gradients (Balbus 2001).

In addition to being dilute, accretion flows about black holes can also be radiatively inefficient: the cooling time from radiation is far longer than the timescale for matter to accrete into the central object. This property requires means, other than radiation (Frank et. al. 2002; Pringle 1981), by which the energy generated through gravitational infall can be lost or outwardly directed (Balbus 2004; Balbus and Hawley 1998).

2 Results and Further Work

We consider the stability of a rotating plasma, with a Keplerian rotation profile, with radial equilibrium temperature and density gradients in the presence of a magnetic field and dynamically important anisotropic viscosities and thermal conductivities – we denote this as the magnetothermal-viscous instability (MVTI). We consider axisymmetric MHD unstable modes in the Boussinesq limit – incompressible flow and isobaric perturbations. Viscous stresses and thermal conductivity are given by their forms in Braginskii (1965).

For physical regimes susceptible to the MVTI, thermal diffusivity arising from electron heat conduction dominates viscous diffusivity. In the plots below, we normalize temperature and pressure gradients $\alpha_T = (v_i/\Omega)\,|\partial \ln T/\partial R|$ and $\alpha_P = (v_i/\Omega)\,|\partial \ln p/\partial R|$, where T and p are temperature and pressure, v_i is the ion sound speed, Ω is the orbital angular velocity, and R is the radial coordinate. We also consider a plasma dilute enough such that $\nu\Omega/v_A^2 > 1$, where ν is the viscous diffusivity and v_A is the Alfvén velocity; in this limit, the maximum growth rate is larger than that of the MRI and is reached at wavelengths $\sim \sqrt{\nu/\Omega} > v_A/\Omega$ (Islam and Balbus 2005).

We find that the effects of anisotropic thermal conductivity increases the maximal growth rate and range of unstable wavenumbers beyond that of the MRI for outwardly decreasing temperatures; for the MRI, the

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maximal growth rate $\Gamma_{\max} = \Omega\sqrt{3}/2$ for a Keplerian rotation profile. These features are demonstrated in Fig. (1). Furthermore, a feature of dilute, geometrically thick nonradiative flows is that in order for the instability to drive accretion, the instability must transport angular momentum and heat flux outwards (Balbus 2004; Balbus and Hawley 1998). Outward flux of angular momentum is demonstrated in Fig. (2) and outward heat flux is demonstrated in Fig. (3). All plots are taken from a linear analysis of the MVTI with purely vertical wavenumbers, $\Omega \propto R^{-3/2}$, and equal toroidal and vertical equilibrium magnetic fields.

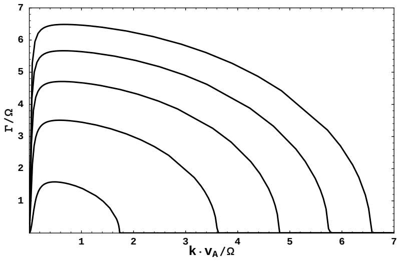

Fig. 1. Growth rate as function of wavenumber for viscosity $\nu\Omega/v_A^2 = 10^4$, with $\alpha_P = 10$ a constant. $\alpha_T = 0$ in the innermost curve and increases outwards in steps of 1.

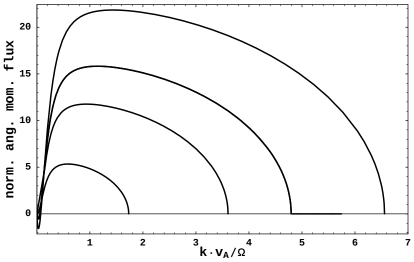

Fig. 2. Normalized angular momentum flux as a function of wavenumber with parameters same as in Fig. (1).

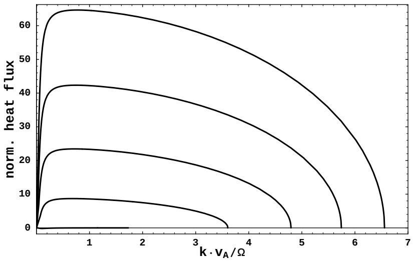

Fig. 3. Normalized heat flux as a function of wavenumber with parameters same as in Fig. (1), but with innermost visible curve $\alpha_T = 1$. In the absence of temperature gradient ($\alpha_T = 0$) there is no heat flux.

A necessary next step involves a stability analysis for a collisionless plasma. Recent work on the collisionless MRI from a kinetic treatment (Quataert et. al. 2002; Sharma et. al. 2003) demonstrates that the features of the collisionless dispersion relation are not substantially different from that found by using a fluid treatment; collisionless damping of long-wavelength modes plays the role of finite collisionality in an MHD plasma. Further work involves the evolution of the MVTI into the nonlinear regime by considering a global simulation of a dilute, nonradiating rotating plasma with both anisotropic viscosity and thermal conductivity in MHD computer codes that explicitly conserve energy, such as ATHENA (Gardiner and Stone 2005). One may consider either a fluid expression of anisotropic viscosity and thermal conductivity or employ approximate expressions, determined from linear kinetic treatments of dilute plasmas anisotropized by a magnetic field (see, e.g., Snyder et. al. 1997), to model collisionless MHD plasmas.

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