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The Physics of Weakly Ionized Protoplanetary Disks

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Protoplanetary disks (PPDs) are gas-rich disks orbiting newly born stars. With a lifetime of a few million years, they are cradles of planets. The gas dynamics of PPDs, including the overall disk structure and long-term evolution, turns out to be crucial to almost all stages of planet formation. See Fig. 1.

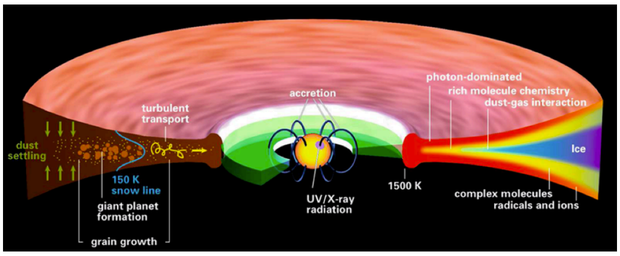

Fig. 1: Sketch of physical processes taking place in protoplanetary disks relevant to planet formation. From [1].

PPDs are magnetized, highly collisional, and very weakly ionized. Correspondingly, the PPD gas dynamics is well described by standard MHD formulation, supplemented by non-ideal MHD effects including Ohmic resistivity, the Hall effect and ambipolar diffusion (AD). They affect the gas dynamics in different ways, and dominate in different regions in disks [2,3]: Ohmic resistivity is important in the densest part of the disk, e.g., the midplane regions of the inner disk. AD dominates in low density regions, including the surface layer of the inner disk and the entire outer disk. The Hall-dominated regime lies in between.

The key to the gas dynamics of PPDs lies in understanding the mechanisms in driving angular momentum transport, which has conventionally been attributed to the magnetorotational instability (MRI, [4]). The MRI taps free energy from differential rotation and saturates into turbulence, which transports angular momentum radially outward [5]. However, it requires the gas to be reasonably well coupled to magnetic field, which is not easily satisfied in the weakly ionized PPDs.

I will review the theoretical and computational studies on PPD gas dynamics over the past thirty years. Early studies have focused on understanding the linear properties of the MRI under individual non-ideal MHD effects. Later works involve MHD simulations concentrated on a local patch of the disk, in the shearing-box framework. More recent works involve 2D and 3D global disk simulations that incorporate all three non-ideal MHD effects.

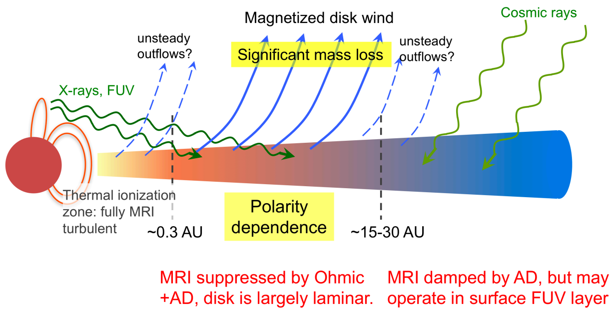

Fig. 2: Current understandings on the gas dynamics of PPDs. Updated from [6].

With these studies, it has been realized that the MRI is largely suppressed or strongly damped in the bulk of PPDs [7,8,9]. Angular momentum transport is instead driven by a magnetized disk wind [8,10], which extracts disk angular momentum vertically [11]. The gaseous disk is largely laminar/weakly turbulent, with complex internal flow structures governed by the radial and vertical magnetic diffusivity profiles [12]. The wind simultaneously drives accretion and outflows, with significant mass loss [12]. Observational evidence and implications on planet formation will also be discussed.

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