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The Formation and Evolution of Protoplanetary Disks: The Critical Effects of Non-Ideal Magnetohydrodynamics

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This review starts with the description of the formation and early evolution of protoplanetary disks. Recent advance in the modeling with resistive magneto-hydrodynamics codes with various numerical techniques has enabled our understanding on the driving of outflows/jets and the formation of circumstellar disks in a self-consistent manner. This provides improved descriptions of the initial condition for the evolution of the disks where planet formation possibly takes place. Magnetic de-coupling due to high density enables massive disks to form and these disks are subject to gravitational instability. The gravitationally unstable region is surrounded by the injection points of the magneto-hydrodynamical outflows during the formation phase of circumstellar disks. In this phase the strong gravitational torque due to self-gravitational spiral arms drives efficient mass accretion onto the central star. Once most of the mass in the disk accreted onto the central star, the self-gravity of the disk becomes unimportant and the mass accretion rate decreases significantly. This later phase corresponds to the classical concept of the protoplanetary disk where the mass accretion may be driven by magneto-rotational instability (MRI). The effect of non-ideal magneto-hydrodynamical effects remain important because of the low ionization degree in protoplanetary disks. Complicated Ohm's law is expected in the regions where dust grains are the main charge carrier. This review outlines some of the complexities, such as non-linear Ohm's law and ionization due to energized electrons. Future work is discussed with the emphasis on the importance of the description of vertical magnetic flux leakage from the disk in global simulation of MRI, since this is ultimately required in the solution of "the magnetic flux problem"of star formation.

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