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Nonlinear Ohm's law: electric heating of plasmas and its effect on MHD in protoplanetary disks

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Non-ideal MHD effects play crucial roles in magnetohydrodynamics (MHD) of protoplanetary disks. It is conventionally assumed that electric fields in the neutral gas rest frame are so weak that they have no effect on the kinetics of ions and electrons. However, a simple order-of-magnitude estimate shows that comoving electric fields associated with MRI-driven turbulence can be strong enough to heat up electrons in some part of protoplanetary disks. We study how the electric heating of electrons affects the ionization state of the disks using a simple chemical reaction model. We find that the heating of electrons results in a reduction of the ionization degree and hence to an enhancement of the magnetic resistivity. This occurs simply because heated electrons collide with grains more frequently than cool electrons. This fact suggests that MRI-driven turbulence may be self-stabilizing, i.e., electric fields accociated with MRI turbulence may kill MRI. We also find that the electric current can become a decreasing function of the electric field strength at such high-field regimes. This "negative differential resistivity" (NDR) is found to destabilize the displacement current, meaning that Ampere's law breaks down even if the fluid motion is nonrelativistic.

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