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Magnetic Coupling in Protoplanetary Disks

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I will review the main ionizing processes at work in protostellar and circumplanetary disks, the chemical reactions controlling the recombination, and the resulting distributions of ionization state and conductivity. A small volume near the central star or planet reaches temperatures above 1000 K, hot enough for collisional ionization of the alkali elements. At high mass flow rates and also around the more massive stars, the gas can even be hot enough for thermal ionization of hydrogen. In the disk's colder outer regions, the ionization is non-thermal and comes from interstellar cosmic rays, stellar energetic protons, X-rays, and UV photons, and the radionuclides found in the dust embedded within the disk gas. The cosmic rays and stellar protons produce showers of energetic particles that ionize the disk at low rates to column depths of about 100 g/cm^2. The X-rays and UV photons ionize at higher rates but penetrate only to about 10 g/cm^2 and less than 0.1 g/cm^2, respectively. The radionuclides yield residual ionization deep inside the disk, beyond the reach of the other effects. The free charges created by these ionizing processes are destroyed by recombination reactions which occur on dust particles in the disk's dense interior, where the grains outnumber the free electrons and ions. Recombination occurs in the gas phase in the atmosphere, where free electrons are so abundant that the grains' charge saturates at the Coulomb limit. Balancing the ionization with the recombination yields the charged particle population and thus the conductivity. The thermally-ionized zone is well-coupled to magnetic fields, with the Ohmic resistivity the largest non-ideal term. The colder regions show a layered pattern. The weakly-ionized interior is subject to Ohmic diffusion, in which collisions decouple all main charge carriers from the magnetic fields, and to Hall drift, in which some of the charged species remain tied to the fields. The atmosphere is better-ionized, but nevertheless poorly-coupled to magnetic fields because the low densities mean low ion-neutral collision rates and thus strong ambipolar diffusion. The ambipolar term is also important far from the star, on the disk's low-density outer fringe.

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