MAGNETIC BRAKING IN WEAKLY IONIZED CIRCUMSTELLAR DISKS

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Recent observations of disk-like mass distributions around newly formed stars have provided evidence for rapid rotation on scales $\lesssim 0.1\,\mathrm{pc}$ with specific angular momenta much higher than typical stellar values. A likely mechanism for the extraction of angular momentum from these regions is magnetic braking by means of Alfvén waves that propagate into the lower-density ambient medium. However, because of the relatively high particle densities ($\gtrsim 10^5\,\mathrm{cm}^{-3}$) and the correspondingly low implied ionization fractions in these apparent disks, their constituent ions and neutrals need not be well coupled to each other and could develop large relative drift velocities. For this reason, previous treatments of magnetic braking that assumed perfect coupling between ions and neutrals have to be modified in this case. In particular, one has to take into account both the *azimuthal* drift that develops because only the ions are directly coupled to the magnetic field and the *radial* drift (or *ambipolar diffusion*) which leads to a redistribution (and leakage) of the magnetic flux. This contribution describes the results of a preliminary analysis of these effects.

The effect of the azimuthal drift is studied with the help of a simple model problem of a two-component disk that is threaded by a uniform magnetic field parallel to the rotation axis. An exact analytic solution for the magnetic braking of the disk is obtained under the assumption that both the ionized and the neutral disk components rotate rigidly and have the same initial angular velocity. In the limit of a low ionization fraction, the neutral disk component is found to brake with an e-folding time given by $\tau_{b,n} = (1+\delta)\tau_{\|,n}$, where $\tau_{\|,n}$ is the nominal braking time of the neutrals due to Alfvén-wave propagation along the field lines. The parameter δ measures the strength of the azimuthal coupling between the ions and the neutrals, and is given by $\delta \equiv \tau_{ni}/\tau_{\|,n}$, where τ_{ni} is the slow-down time of a neutral due to collisions with ions. In the limit $\delta \ll 1$ (*strong coupling*), the angular velocities of the two disk components are nearly equal at all times, whereas in the $\delta \gg 1$ limit (*weak coupling*) the ion angular velocity rapidly declines to a fraction δ^{-1} of the neutral angular velocity. This difference in the rotation velocities is potentially detectable by high-resolution observations of molecular-line tracers such as HCO^+ and HCN. It is shown that equilibrium configurations of self-gravitating disks necessarily correspond to the strong-coupling regime, but that low-mass disks that are formed in the gravitational field of a central star can, in principle, have a large value of δ.

The results of the azimuthal-drift analysis are incorporated into another model problem that focuses on the effect of the radial drift. Through a set of numerical calculations, it is demonstrated that the relative importance of ambipolar diffusion in the braking process is determined by the parameter $\epsilon \equiv \tau_d/\tau_{b,n}$, where τ_d is the characteristic ambipolar-diffusion time. It is argued that the radial ion-neutral drift is unlikely to interfere strongly with magnetic braking in contracting, self-gravitating disks because the latter must satisfy $\epsilon \gg 1$ so long as the external-to-internal density ratio is not very small ($\gtrsim 10^{-3}$). By contrast, it is shown that in circumstellar disks with negligible self-gravity, ambipolar-diffusion effects could influence the braking process even for relatively large density ratios.

As expected, ambipolar diffusion is found to reduce the efficiency of magnetic braking by decreasing the flux-to-mass ratio in the disk and thereby increasing $\tau_{\|,n}$. The initial effect of diffusion in the weak-coupling limit could, nevertheless, be to accelerate the braking process by inducing a contraction that increases the density in the disk and thereby reduces τ_{ni}. (Radial contraction induced by the loss of centrifugal support may, in turn, serve as a catalyst for ambipolar diffusion.) However, flux leakage should cause the disk to evolve towards the strong-coupling regime where the only effect of diffusion would be to slow down the braking process. Several additional aspects of the disk evolution are discussed, and the need for more extensive numerical calculations is emphasized.