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NONADIABATIC SCATTERING AND TRANSPORT AT THE SPINDLE CUSP

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When magnetohydrodynamics is used to describe plasma flow across a separatrix to open field lines, the transport is modeled by a diffusion equation with a sink for particles on the open lines. In that case, it is assumed that plasma is carried to and from the separatrix by diffusive processes. The purpose of this note is to discuss the nonadiabatic processes occurring at a spindle cusp to transfer plasma across a separatrix. After an ion is delivered to the vicinity of the separatrix by diffusion it enters the spindle cusp and will skip back and forth across the separatrix, producing a structured transport not seen with MHD.

To illustrate the motion of ions across a separatrix, let us consider a cylindrical magnetic field of the form

$$B_r(r,z) = -\frac{\partial A_\theta}{\partial z} \quad ,$$

$$B_z(r,z) = \frac{1}{r}\frac{\partial(rA_\theta)}{\partial r} \quad . \tag{1}$$

The magnetic flux passing through any circle concentric with the axis and having radius r is

$$\psi = 2\pi r A_\theta(r,z) \quad .$$

Since B_z changes sign at $z = 0$, ψ must also have odd parity at $z = 0$ and is defined by

$$\psi > 0 \text{ for } z < 0 \text{ and } r > 0 \quad ,$$

$\psi = 0$ for $z = 0$ and/or $r = 0$,

$\psi < 0$ for $z > 0$ and $r > 0$. (2)

Therefore, a simplified spindle separatrix is defined by the z axis and $z = 0$ plane. The Lagrangian of a particle in this field with an azimuthally symmetric electrostatic potential, ϕ, is

$$L = \frac{1}{2} mv^2 - q\phi + qA_\theta v_\theta \quad . \tag{3}$$

The canonical angular momentum is

$$p_\theta = mr^2\dot{\theta} + qrA_\theta \tag{4}$$

We note that p_θ is a constant of the motion since $\frac{\partial L}{\partial \theta} = 0$. Let us define the ψ value for any particle as $\psi(r_g, z_g)$ where the guiding center moves on a surface (r_g, z_g) as long as the magnetic moment, $\mu = T_\perp/B$, is preserved in adiabatic motion.

After some brief manipulations one can express p_θ as a function of ψ and μ for particles in adiabatic motion near the axis

$$p_\theta = \frac{q}{2\pi} \psi - \frac{m}{q} \mu \quad , z < 0$$

$$p_\theta = \frac{q}{2\pi} \psi + \frac{m}{q} \mu \quad , z > 0 \quad . \tag{5}$$

Eq. (5) is consistent with the simultaneous invariance of p_θ, ψ, and μ away from the spindle point, $r = z = 0$. However, only p_θ is invariant in the vicinity of the spindle point. Equations (2) and (5) lead to the following restrictions on p_θ

$$p_\theta > -\frac{m}{q}\mu_M \text{ for } z < 0 \quad ,$$

$$p_3 < \frac{m}{q}\mu_M \text{ for } z > 0 \quad . \tag{6}$$

where μ_M is the maximum magnetic moment that can be anticipated for particles of given kinetic energy. Consequently there is a range of flux surfaces between which particles may freely scatter at the spindle cusp

$$-\frac{2\pi m}{q^2}\mu_M < \psi < \frac{2\pi m}{q^2}\mu_M \quad . \tag{7}$$

For example, an ion coming from the left. $z < 0$, with ψ satisfying Eq. (7) may cross the separatrix and move along the positive z axis or be deflected away from the axis near the $z = 0$ plane. In time the same ion may be mirrored back to the spindle cusp and repeat the "scattering" as long as Eq. (7) is satisfied.

In conclusion, we have identified a collisionless process that can transfer ions and electrons across a separatrix at a spindle cusp. This "scattering" has a limited range of penetration into the plasma, given by Eq. (7) in flux coordinates. Since the range in ψ is proportional to the particle mass, ions will be scattered over a much wider region than electrons. Electron transport will be governed primarily by standard diffusive processes but a significant new factor has been added to ion transport in a spindle cusp.

Computer codes are being written to elucidate this nonadiabatic particle behavior near the spindle cusp. We expect to extend these concepts of particle scattering across the cusp plane by using a more realistic flux profile. We can then realistically quantify the scattering process by actually following individual particle orbits through the static cusp region. Particle and angular momentum transport probabilities through the cusp region can be determined in this way.