STABILITY OF AN ANISOTROPIC PLASMA JET

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Abstract. The instability arising in a slab model of a jet moving in an external plasma is investigated, assuming the plasmas to be governed by the Chew, Goldberger, and Low (CGL) equations. Numerical results on the growth rates of unstable modes are obtained both for symmetric and asymmetric perturbations for equal aligned and transverse fields in wide and slender jet approximations. Special cases of an incompressible jet moving in a static CGL plasma and of a CGL plasma jet moving in an incompressible environment are also considered and conditions of instability derived.

1. Introduction

It is well-known that several situations arise in astrophysics where a jet of plasma moves past a stationary external plasma, e.g., in comet tails, in the solar corona, photospheric flux tubes, during enhanced solar wind emission at the time of high solar activity and in extragalactic radio sources. Observations have revealed that though the inside flow in photospheric flux tubes is essentially negligible, the outside fluid flows with a speed typically of the order of $1 - 3 \text{ km s}^{-1}$. High-speed jets in the solar atmosphere such as surges in H$\alpha$ (Roy, 1973) or Brueckner’s jets observed in EUV (Brueckner and Bartoe, 1983) are known to occur in relation to the appearance of a bright point in active regions. These jets are ejected with typical speeds of a few hundred km s$^{-1}$ and occasionally show helical motion around the axis of ejection. Similarly recent observations of time series of soft X-ray telescope images (Shibata, 1992) have established the existence of many X-ray jets in the solar corona. The typical size of these jets is about $5 \times 10^9 - 4 \times 10^5 \text{ km}$ with translation velocity in the range of $30 - 300 \text{ km s}^{-1}$.

Again observations show many extragalactic jets with large oscillations in the plane of the sky, e.g., 3C449 (Perley, Willis, and Scott, 1979), NGC 6251 (Perley, Bridle, and Willis, 1984), ad Cygnus A (Dreher, Carilli, and Perley, 1987) consistent with sinusoidal or helical structure that grows to large amplitude.

The astrophysical jets interact in a substantial way with their environments. This interaction plays an important role in determining the dynamics and morphology of jets. High-resolution observations have revealed that radio jets, in many cases, are initially very straight and well-collimated but disrupt and bend abruptly in the galactic halo. This is most likely due to some form of instability (e.g., Kelvin–Helmholtz instability) arising in jets. Consequently several studies have recently been made to investigate the problem of stability of plasma jets either in the form of a cylinder or a slab (Gill, 1965; McKenzie, 1970; Ershkovich and Nusinov, 1972;

All these investigations made use of the collision-dominated, single-fluid hydro-magnetic equations with scalar gas pressure approximation for a description of the plasma. This assumption is not likely to hold true in dilute plasmas where, in fact, the plasma pressure is anisotropic due to infrequent collisions, having two scalar components, one parallel and the other perpendicular to the ambient magnetic field. The plasma is then described by the modified single-fluid equations known as the CGL equations (Chew, Goldberger, and Low, 1956) where the independent components of anisotropic pressure are determined by the two adiabatic equations of state instead of the single equation of state of the ideal MHD theory. It is therefore, of interest to investigate the problem of the stability of an anisotropic plasma jet (the CGL jet), and this forms the object of the present paper.

2. Equations of the Problem

Consider a plasma slab of uniform density, $\rho_1$, and thickness, $2l$, in relative motion with the surrounding plasma of uniform density $\rho_2$. The plasmas in the slab region $-l \leq Z \leq l$ and the external region $|Z| > l$ are assumed to be embedded with uniform magnetic fields $B_1$ and $B_2$ respectively both in the $XY$-plane, which render the plasma pressure anisotropic so that it has different values of components along and perpendicular to the prevalent magnetic field.

The initial steady state of the configuration requires that $\nabla \cdot p = 0$ for either region. Here $p$ denotes the tensorial plasma pressure having constant components $p_{\parallel}$ and $p_{\perp}$ along and normal to the field. The equilibrium at each interface $|Z| = l$ is maintained by the pressure balance equation

$$p_{\perp 1} + \frac{B_1^2}{8\pi} = p_{\perp 2} + \frac{B_2^2}{8\pi}. \quad (1)$$

To investigate the stability of the initial state we assume the CGL plasma in either region to be subject to a first-order velocity perturbation, $u$, of the form (some function of $Z$) $\times \exp (ik_x x + ik_y y + nt)$. Let the corresponding perturbations in other physical parameters be $\delta \rho$, $\delta p_{\parallel}$, $\delta p_{\perp}$, and $b$. Taking the ambient magnetic field, $B_0$, to be along the $x$-direction for the CGL plasma in either region, the linearized perturbation equations are written as

$$\rho_0 n_0 u = -\nabla \cdot \delta p + \frac{1}{4\pi} (\nabla \times b) \times B_0, \quad (2)$$

$$n_0 \delta \rho = -\rho_0 \nabla \cdot u, \quad (3)$$

$$n_0 b = -B_0 \nabla \cdot (u \dot{x} + ik_x B_0 u), \quad (4)$$