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Dynamo transformation of the collisional R-T in a weakly ionized plasma

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Abstract. Theoretical prediction of a new kind of normal mode behaviour of electro-mechanical nature was first time reported by Dwivedi and Das in 1992 in the context of mesospheric modeling of observed neutral induced turbulence. Local dynamo action (due to relative neutral flow) governs the basic physical principle for linear excitation of the neutral induced low frequency instability (NILF) in mesospheric plasma, which comprises of weakly ionized inhomogeneous gas confined by the external gravity and ambient magnetic field. The present contribution offers physical explanation in terms of dynamo transformation of neutral drag effect as a source to understand complete suppression of the usual collisional R-T and in turn linear driving of the NILF. It is therefore emphasized, worth calling it as the dynamo instability.

Keywords. Ionosphere; mesosphere; partial ionization; irregularities; collisional; dynamo.

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1. Introduction

Low temperature plasmas are often coupled to neutral population through charge exchange or elastic collisions. The edge and divertor region of toroidal plasmas and the ionosphere are a few well known examples. Similar situations are also likely to occur in weakly magnetized and unmagnetized plasmas such as near the stagnation point of the heliosphere where the interstellar neutrals undergo charge exchange collisions with ions in the solar wind [1]. The presence of neutrals in plasmas can drive new instability in many ways. For example the collisional Rayleigh-Taylor (R-T) instability is driven by the combined effects of external gravity and density gradients but requires ion-neutral collisions to proceed. It is thus well known that dissipation can allow certain instabilities to proceed that would not otherwise occur [2]. In most of theoretical analyses neutral dynamics is ignored and is assumed to form an immobile background.

In the context of mesospheric modeling of neutral induced turbulence [3,4] Dwivedi and Das [5] were the first to point out the possibility of a new kind of low frequency irregularity involving plasma and neutral fluid dynamics. Its driving mechanism was found to be based on the dynamo principle of a.c. generator. However, a pertinent question remains to be addressed: what happens to the collisional R-T? Present contribution will address this question to illustrate the fate of collisional R-T under the consideration of neutral dynamics.

2. Dynamical coupling of plasma and neutrals

2.1 *Collisional interchange instability and NILF instability*

Normally neutral dynamics is ignored while describing the normal mode behaviour of the weakly ionized/partially ionized plasmas (WIP/PIP). In equilibrium it is justified by the hydrostatic approximation or by the choice of the neutral frame of reference as a basis frame to carry out the normal mode description of the partially ionized plasma. In perturbation, the neutral fluctuations are ignored by assumption that the normalized neutral fluctuation $(\tilde{n}_a/n_{a0})$ is much smaller than that of the plasma fluctuation $(\tilde{n}_p/n_{p0})$ i.e. $\tilde{n}_a/n_{a0} \ll \tilde{n}_p/n_{p0}$. Recently Daughton *et al* [6] have carried out a theoretical analysis for interchange type instability driven by neutral pressure gradient in the context of divertor regime of magnetically confined torroidal plasma. The author refutes their claim for first time reporting of the neutral dynamic response to plasma perturbations as we [5,7] already published that in the context of mesospheric modeling of WIP/PIP. In our earlier publications [5,7], it has been argued that on wave time scale of interest the static response of the neutrals becomes questionable. Thus a deviation from hydrostatic approximation causes dynamical equilibrium of diffusive type to be setup.

Now let us have an overview of the conventional R-T and the NILF mode. The growth rate (γ_{R-T}) for the usual collisional R-T is given as

$$\gamma_{R-T} = \frac{g}{\nu_{iaL_p}} \quad \text{for} \quad \kappa g < 0, \tag{1}$$

where ν_{ia} is the ion-neutral collision frequency and g is the acceleration due to external gravity. L_p is the scale length of plasma density inhomogeneity and κ is the measure of inverse plasma density gradient scale length. For the case of NILF mode the growth rate (γ_N) and the growth condition are given as,

$$\gamma_N = \frac{k_\perp^2 c_a^2}{\nu_{ai}} \left| \left(1 - \frac{c_a^2}{L_a g}\right) \right| \quad \text{for} \quad \frac{c_a^2}{L_a g} > 1 \quad \text{and} \quad L_a g > 0. \tag{2}$$

Here c_a denotes for thermal speed of the neutral atoms and L_a is the neutral density gradient scale length. ν_{ai} is the neutral-ion collision frequency whereas $k_\perp$ denotes for the wave vector. It is obvious to note the difference between usual R-T and NILF mode of instabilities. Now let us consider a situation when the relative neutral flow produces an internal effective gravity in the equilibrium but is not perturbed by the resulting instability. For a quick estimation of the growth rate of the resulting instability due to internal effective gravity let us derive its expression as

$$g_I^{\text{eff}} = \nu_{i\alpha}(v_{a\perp} - v_{i\perp}) = \frac{\nu_{ia}}{\nu_{ai}} g \left(1 - \frac{c_a^2}{L_a g}\right). \tag{3}$$

Now the growth rate (γ_I) for internal effective gravity driven interchange type instability can be directly written as

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$$\gamma_I = \frac{g_I^{\rm eff}}{\nu_{ia} L_p} = -\frac{g}{\nu_{ai} L_p}\left(1 - \frac{c_a^2}{L_a g}\right). \tag{4}$$

Here the minus sign indicates the direction of the internal effective gravity, which is opposite to the external gravity. Now in the absence of the external gravity, the above expression reduces to

$$\gamma_I = \frac{c_a^2}{\nu_{ai} L_p L_a}. \tag{5}$$

This is the expression for the growth rate of the neutral pressure gradient driven instability in the absence of external gravity [6] and the growth condition demands $L_p L_a > 0$.

2.2 *Review of local normal mode analysis of NILF instability*

Now we will try to understand the elimination of the internal collisional R-T instability due to neutral pressure gradient under the influence of neutral fluctuations and external gravity. For this below given equations are needed for critical illustration of the subject under slab geometry model which assumes that the ambient magnetic field is directed along z-direction (North-South direction), plasma and neutral density gradients are in x-direction which corresponds to vertical direction. The wave propagation is in x-y plane, where the y-direction corresponds to East-West. This is shown in figure 1.

Divergence free current equation

$$\nabla \tilde{n}_i \cdot \frac{\vec{g}_I^{\rm eff} \times \hat{z}}{\omega_{ci}} - \frac{\nu_{i\alpha}}{\nu_{\alpha i}} \frac{c_a^2}{\omega_{ci}} \frac{\nabla_\perp n_{i0}}{n_{a0}} \cdot \nabla_\perp \tilde{n}_a \times \hat{z} = 0. \tag{6}$$

Assuming the fluctuations to vary as $\exp(-i\omega t + ik_x\hat{x} + ik_y\hat{y})$, the Fourier analysis of equation (6) gives rise to

$$\frac{\tilde{n}_a}{n_{a0}} = -\frac{gL_p}{c_a^2}\left(1 - \frac{c_a^2}{L_a g}\right)\frac{\tilde{n}_i}{n_{i0}}. \tag{7}$$

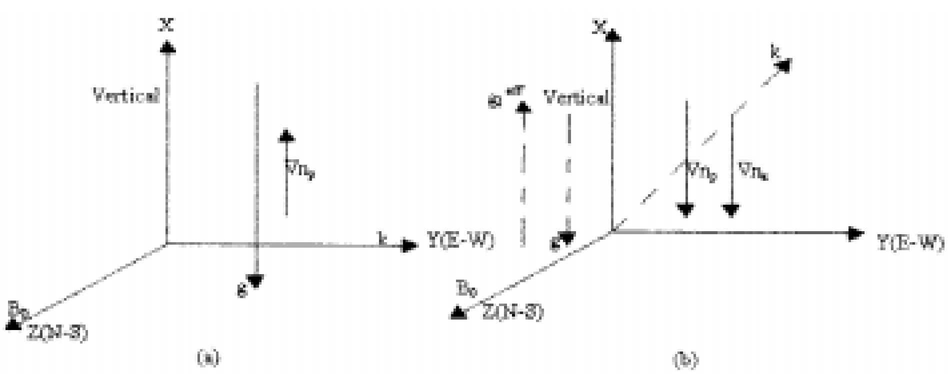

Figure 1. Model slab geometry for usual R-T (**a**) and NILF- mode (**b**).

Now using plasma approximation, the electron continuity equation yields

$$\frac{\tilde{n}_i}{n_{i0}} = \frac{\tilde{n}_e}{n_{e0}} = \frac{\tilde{n}_p}{n_{p0}} = -\frac{c}{B_0}\frac{k_\perp}{\omega}\frac{\tilde{\phi}}{L_p}. \tag{8}$$

Again the neutral continuity equation reads as;

$$\begin{aligned}\frac{\partial}{\partial t}\left(\frac{\tilde{n}_a}{n_{a0}}\right) &+ \left[-\frac{c}{B_0}\hat{z}\times\nabla_\perp \ln n_{a0}\cdot\nabla_\perp\tilde{\phi} + \frac{\nu_{ia}\nabla_\perp\tilde{n}_a}{v_{ai}n_{a0}}\cdot\frac{\vec{g}\times\hat{z}}{\omega_{ci}}\right.\\ &\left. + \frac{1}{\nu_{\alpha i}}\left(\frac{\nabla_\perp\tilde{n}_a}{n_{a0}}\cdot\vec{g} - \frac{c_a^2}{n_{a0}}\nabla_\perp^2\tilde{n}_a\right)\right]\\ &+ \frac{c_i^2}{\omega_{ci}}\left[\nabla_\perp \ln n_{a0}\times\hat{z}\cdot\frac{\nabla_\perp\tilde{n}_p}{n_{p0}}\right.\\ &\left. + \hat{z}\times\nabla_\perp \ln n_{p0}\cdot\frac{\nabla_\perp\tilde{n}_a}{n_{a0}}\right] = 0.\end{aligned} \tag{9}$$

The linear local dispersion relation for the NILF mode of instability can be deduced by eqs (7)–(9) in the following form [7]:

$$\begin{aligned}\omega + \frac{k_y g}{\omega_{ci}}\frac{\nu_{ia}}{\nu_{ai}}&\left[\left(1-\frac{c_a^2}{L_a g}\right)\left(1-\frac{k_x}{k_y}\frac{\omega_{ci}}{v_{ia}}\right) - \frac{\nu_{ai}}{\nu_{ia}}\frac{c_i^2}{L_p g}\right]\\ &+ i\left(1-\frac{c_a^2}{L_a g}\right)\frac{k_\perp^2 c_a^2}{\nu_{ai}} = 0.\end{aligned} \tag{10}$$

All the notations are standard and are defined in [5,7] with some difference in a few notational representations. As discussed earlier, the growth condition demands that the relative neutral flow should be directed against the external gravity and plasma-neutral density gradients. It seems the variation in internal effective gravity due to neutral perturbation causes self-immolation of the usual R-T. In turn the neutral fluctuation response to plasma perturbation under external gravity leads to excitation of a new mode of neutral induced turbulence in WIP/PIP. A few more papers have been written to highlight the importance of the neutral response dynamics to low frequency electromagnetic fluctuations [8–11]. Historical descriptions of earlier efforts have been given in [6]. This is to emphasize that the instability reported by Dwivedi and Das in 1992 could be seeded by a vertical tilt [12] in neutral wind or by gravity wave motions in vertical direction [13]. In our earlier treatment [5,7] the importance of governing dynamo principle to amplify the neutral induced low frequency electro-mechanical fluctuation in WIP/PIP makes a case to call it as dynamo instability in general.

3. Dynamo interpretation of the NILF instability

The excitation mechanism of the NILF instability is based on the dynamo principle as already discussed in the previous publications. Figure 2 depicts the intermediate steps involved in the dynamo interpretation of the NILF mode of instability. In conclusion it

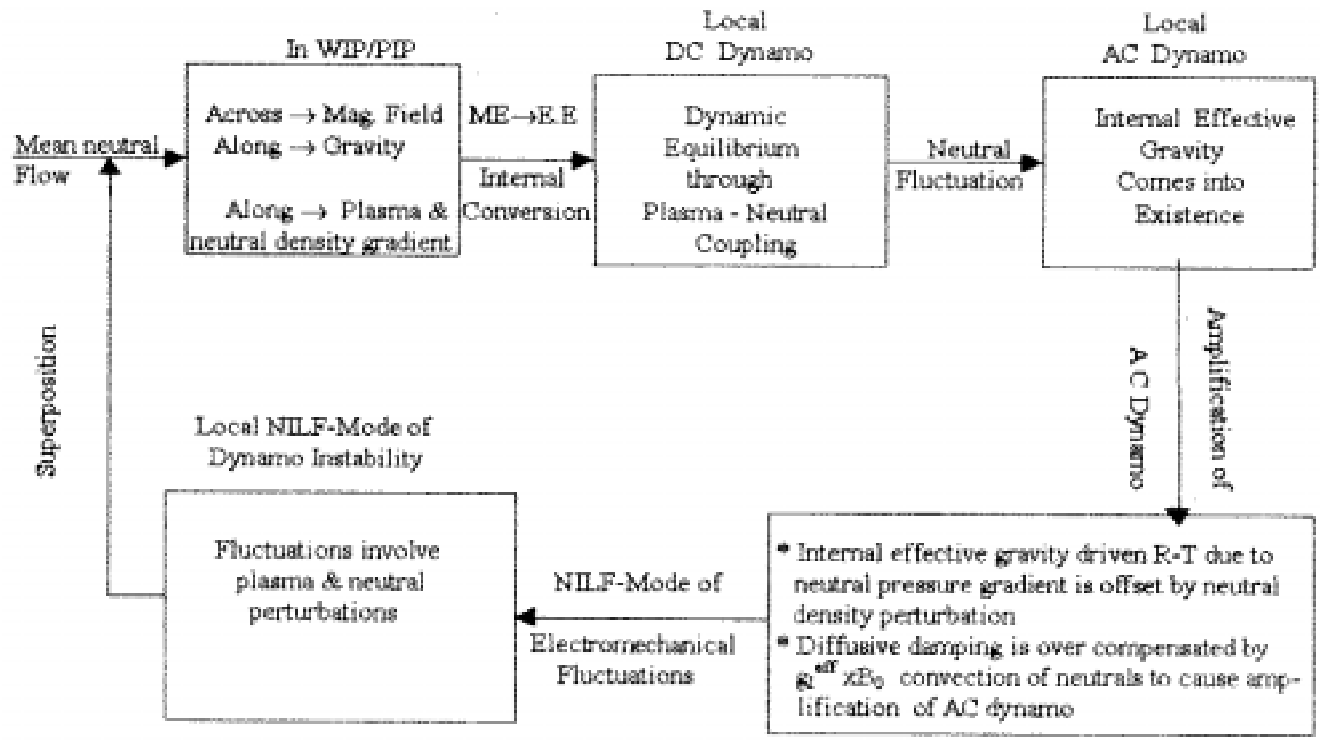

Figure 2. Dynamo description on NILF-mode of electro-mechanical fluctuations in WIP/PIP. Here ME stands for mechanical energy and EE for electrical energy.

is asserted that the NILF mode of instability as reported by Dwivedi and Das in 1992 forms a novel mode of neutral induced turbulence in WIP/PIP under external gravity. As described in earlier sections, the usual R-T is suppressed and in turn leaves a scope for NILF instability to occur. The future course of work will consider a non-stationary response [14] of the neutral equilibrium to further ascertain the existence of the above mentioned dynamo instability.

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