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Diamagnetic GAM Drive Mechanism

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Introduction

Geodesic Acoustic Modes (GAM), poloidal flows oscillating at the characteristic acoustic frequency of a tokamak or stellarator, are an ubiquitous edge plasma phenomenon in magnetic fusion devices [1, 2]. In recent years they have dramatically gained experimental interest and are candidates for applications ranging from plasma diagnostics [3] to transport control [2].

GAMs and the somewhat better known stationary Zonal Flows arise as the two linear eigenstates from the coupling of perpendicular plasma rotation and parallel sound waves by magnetic inhomogeneities such as due to toroidal curvature. Both have virtual no radial velocity component whence they are in practice completely stable against any radial pressure gradients. Although the stationary Zonal Flows have been suggested by theory to be predominantly driven by turbulence somewhat earlier than the GAMs, the latter were detected first in experiments due to their clear signature of a rather well defined frequency.

GAMs oscillate between states of poloidally homogeneous rotation and (for a tokamak) up-down antisymmetric plasma compression. Hence, at first glance the natural turbulent drive (or damping) mechanisms for them seem to be either a direct boost of the rotation – via Reynolds stress – or the creation of antisymmetric pressure distributions – by vertical oscillations of the turbulent heat transport – which may both be synchronised with the flow oscillation by its shearing action.

Principle mechanism

However, an up-down antisymmetric pressure may also be created by the turbulence more indirectly if it perturbs the ion diamagnetic drift velocity, e.g., by radially local flattening of the overall pressure gradient. Due to the inhomogeneous magnetic field the perturbed ion diamagnetic flow (and diamagnetic heat flow) will exhibit an up-down antisymmetric divergence which creates a pressure perturbation exciting the GAM. (While the diamagnetic flows of the electrons have exactly the opposite divergence, their asymmetries are swiftly erased due to the much greater electron mobility along the magnetic field lines.)

This obviously requires a diamagnetic velocity modulation in resonance with the GAMs, and thus a modulation of the flux surface averaged turbulent transport in the proper phase relation with the oscillating flow. On the other hand, a modulation of the turbulent transport due to the

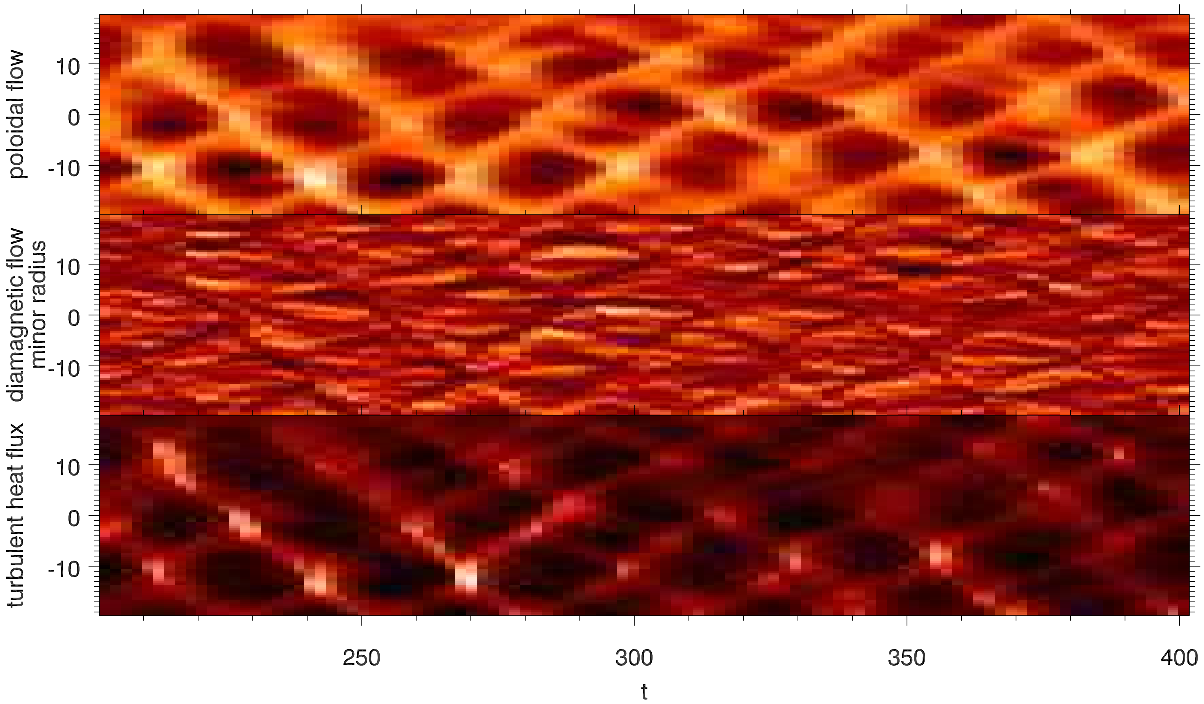

Figure 1: Color coded plots of GAM poloidal flow velocity (top), ion diamagnetic velocity (middle), ion heat flux (bottom) versus time and minor radius from a fluid turbulence simulation for parameters from the transitional regime [4]. $k_{r,max} = 0.4$ taking $\beta \sim 3\chi$, where χ is the heat diffusivity, which corresponds to a preferred GAM-Wavelength of about 20 in the units of this figure.

GAMs themselves is expected to happen in the tokamak edge, and has been observed early on in simulations [4] and recently in many experiments [5].

In the simulations [4] it was found that the turbulent transport is modulated by the shear flow such that it essentially proportional to the local flow velocity in electron diamagnetic direction. This may be described by the empirical relation (obeying Gallilean invariance in θ)

$$\delta Q = \gamma \partial_r^2 (Q - \alpha v_\theta + \beta v_{di}). \tag{1}$$

with appropriate empirical constants α, β, γ. The inverse contribution from v_{di} has been added, since the transport is reduced if the ion diamagnetic velocity goes up, i.e., if the gradient decreases. γ is typically rather large, so that essentially $\delta Q \approx \alpha v_\theta - \beta v_{di}$. From the radial heat transport balance one obtains a modulation of the local ion diamagnetic velocity equal to

$$-i\omega \delta v_{di} = -i\omega \partial_r \delta p_i = -\frac{2}{3}\partial_r^2 \delta Q = -\frac{2\alpha}{3}\partial_r^2 v_\theta + \frac{2\beta}{3}\partial_r^2 v_{di}, \qquad \delta v_{di} = \frac{2i\alpha k_r^2 v_\theta}{3\omega + 2i\beta k_r^2} \tag{2}$$

in the usual dimensionless units. Disregarding for simplicity the diamagnetic heat flow, the coupling to sound waves, the Reynolds stress, and the up-down antisymmetric transport component

[2], the GAM velocity obeys the equation

$$\omega^2 v_\theta = \omega_{GAM}^2 (v_\theta + \delta v_{di}), \quad (3)$$

resulting in the dispersion relation

$$\omega^2 = \omega_{GAM}^2 \left(1 + \frac{2i\alpha k_r^2}{3\omega + 2i\beta k_r^2}\right) \Rightarrow \omega \approx \omega_{GAM} + i\frac{3\alpha k_r^2}{9\omega_{GAM}^2 + 4\beta^2 k_r^4} + \frac{2\alpha\beta k_r^4}{\omega_{GAM}(9\omega_{GAM}^2 + 4\beta^2 k_r^4)}. \quad (4)$$

The imaginary component indicates growth of the GAMs provided that α is positive, i.e., that local poloidal flows in electron (ion) diamagnetic direction are accompanied by maxima (minima) of turbulent transport (as was observed computationally [4] and experimentally [6]).

The growth rate in Eq. 4 exhibits a maximum at a wavenumber $k_{r,max} = \sqrt{3\omega/(2\beta)}$ depending on the sensitivity β of the turbulence to the gradients (essentially the differential diffusivity, about 2-3 times the turbulent diffusivity). Nonlinear effects beyond this toy model, the other two turbulent drive/damping terms mentioned above and dissipation likely will reduce the growth rates overall while still basically conserving the wavelength scaling.

Fig. 1 shows a flux surface averaged flow velocity, ion diamagnetic velocity, ion heat flux versus time and minor radius from a fluid turbulence simulation for parameters from the transitional regime [4]. Note the characteristic diamagnetic-velocity double-layers caused by the ion heat flux modulation in phase with the GAMs. About 30% of the GAM-drive in this case stem from the diamagnetic velocity modulation.

Whether the above mechanism is an effective driver of the GAMs depends on the strength of the transport modulation, the geometry controlling the importance of the diamagnetic drifts, and the ratio of turbulence time scales and GAM frequency. It is however persuasive that the estimate of the GAM wavelength derived from the above argument agrees with the observed one. In turbulence simulations for edge parameters, the described effect tendencially is a strong driver of the GAMs of equal importance to the other two.

Consequences

As a striking consequence, the coupling of diamagnetic velocity and GAM can produce propagating fronts of high flow velocity and transport, which closely resemble avalanches – without necessity of a critical gradient: Fig. 2 shows the time evolution of an initially isolated single GAM peak (with turbulence) for identical background parameters as Fig. 1. The diamagnetic flow drive is strong enough to advance the flow and transport layer in radial direction (the preferred wave-number derived above fixes the phase velocity considering that the GAM frequency is mostly determined by linear physics) – although the linear dispersion relation would just result in a localised oscillation!

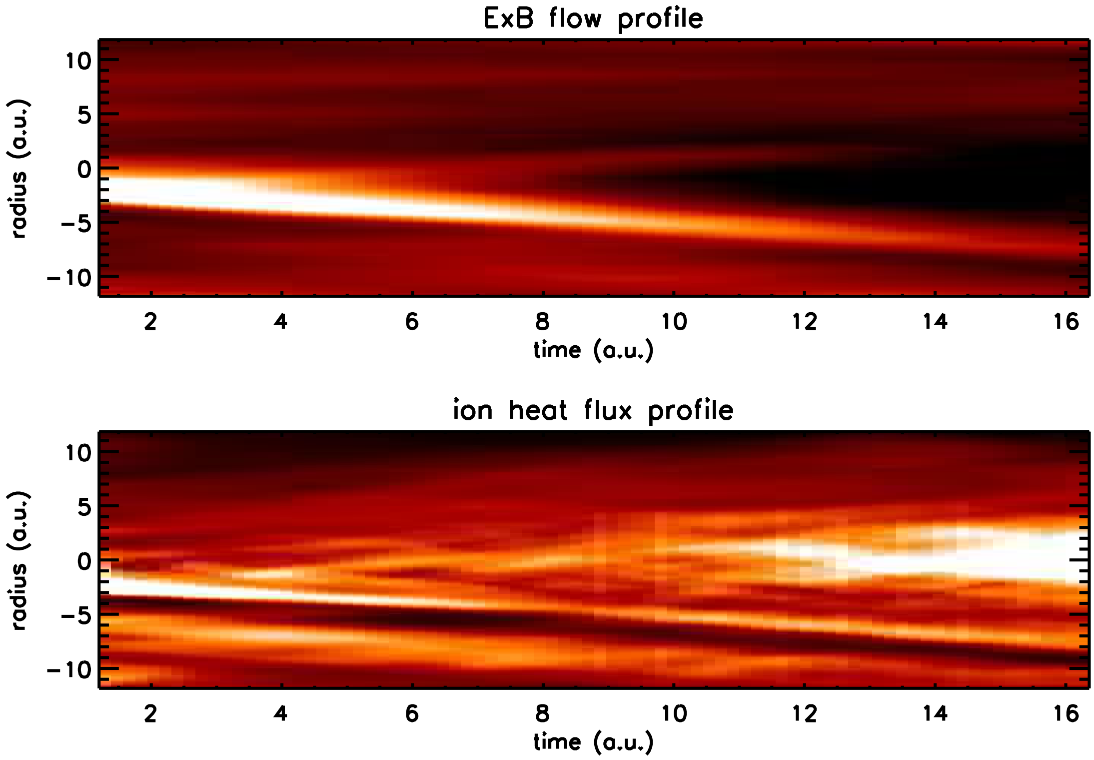

Figure 2: plots of flow (top) and turbulent heat flux (bottom) for the time evolution of an initially isolated single GAM peak

An interesting feature of the diamagnetic drive mechanism is that it offers the possibility of direct excitation of GAMs by resonantly modulated external heating (replacing turbulent transport in (1) with heating power). If the GAMs are detected by Doppler reflectometry, the achievable efficiency is certainly enough for diagnostic purposes such as to *actively* probe the GAM frequencies or to measure the turbulence response to the GAMs. Particularly exciting however is the prospect of a way to *artificially* set up a GAM pattern to control the transport.

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