Drift Waves in the Solar Corona

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ABSTRACT

The heating of the solar corona is still an unanswered puzzle for solar physicists. Magnetic reconnection and wave heating models relying on MHD simulations are generally invoked to explain the coronal heating, which ignore some of the physics that occurs due to the interaction between ions and electrons. In the present work we turn to drift waves as a new candidate for the plasma heating mechanism in the solar atmosphere. We employ a two-fluid model (COOLFluiD) to the simulate the solar corona environment and provide a driving mechanism for the drift waves, i.e. a density gradient perpendicular to the ambient magnetic field. The model includes ions and electrons as separate species. We explore the effect that the scale of the density inhomogeneity presents in driving the waves. Most importantly we are interested in the heating effect of the plasma that the drift waves generate, the growth rate of the density modulation, and the transport effects that occur in the plasma due to the drift wave instability.

Motivation

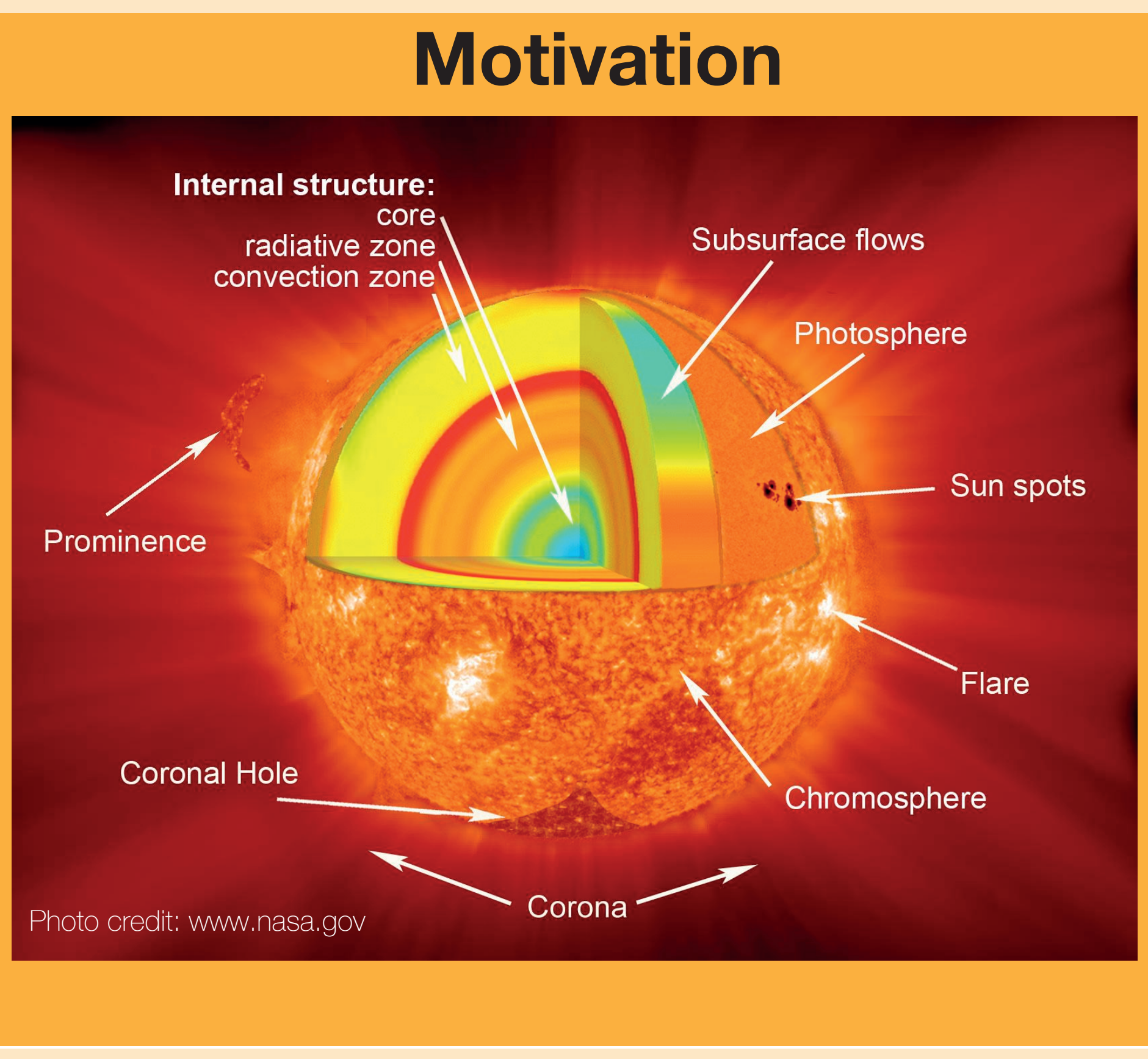


Photo credit: www.nasa.gov

Coronal Heating Problem

* Observations in the 1940s showed for the first time that the temperature in the solar corona is ~ 1MK, inferred from highly ionized atoms
* However, in the photosphere T~6000K and even lower in the sunspots! (~4800K)

Why and how can the temperature in the solar atmosphere increase ~ 200 times!?

* In addition, radiative losses by UV emission would cool the corona in hours – days.
* A source of continuous heating is needed to achieve the observed temperatures!

Key ingredients for a successful coronal heating model

A successful model should:
1. provide a source of energy large enough to account for extremely high temperatures observed
2. efficiently transfer/convert energy from the source to the plasma particles in the corona
3. explain the observed temperature anisotropy ($T_\perp > T_\parallel$, where the directions are w.r.t. the magnetic field)
4. demonstrate the ion and electron temperature discrepancy ($T_i > T_e$)
5. result in higher temperature for heavier ion species
6. should work everywhere in the corona and should take into account the lower layers in the solar atmosphere
7. should explain how heating occurs at different length scales
8. should provide the necessary heating rates for different regions in the corona:

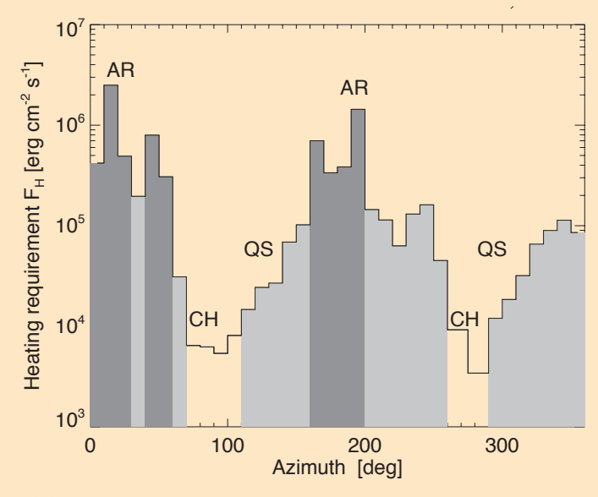
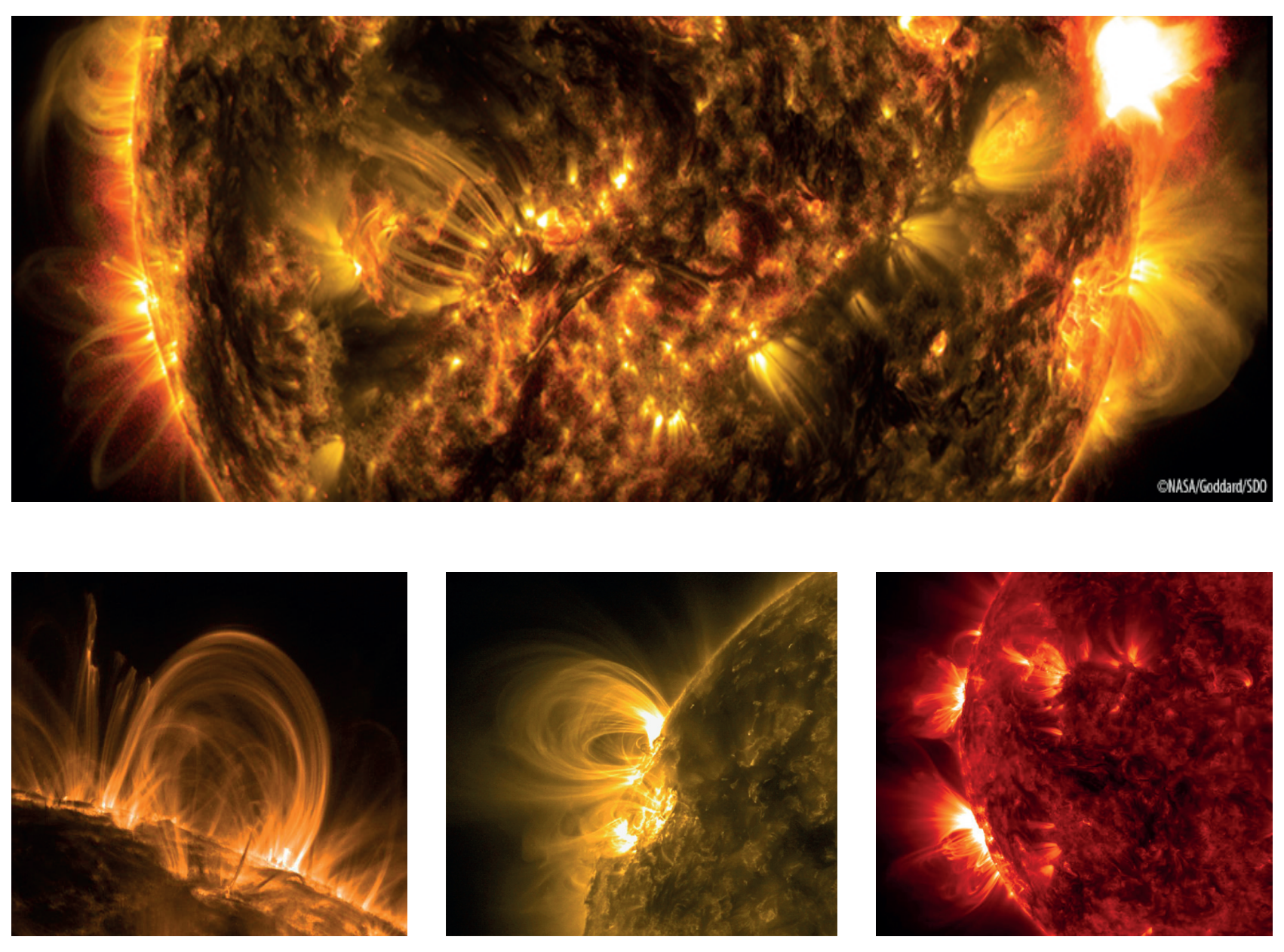


Figure 9.1: Composite soft X-ray image of the Sun observed on 1992 Aug 26 with Yohkoh (*top panel*). The histogram shows the heating rate requirement (*bottom panel*) in the 36 azimuthal sectors around the Sun. The labels indicate the locations of active regions (AR; dark grey), quiet Sun regions (QS; light grey), and coronal holes (CH; white) (Aschwanden 2001b).

We propose drift waves as a candidate to explain coronal heating

Short overview of drift waves

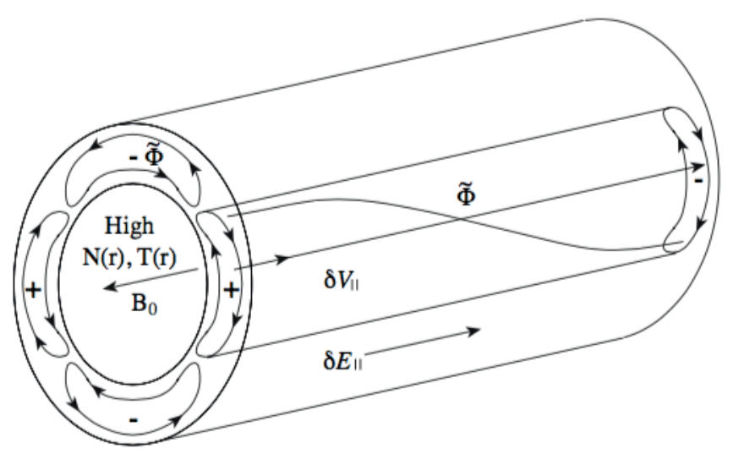
drift - > diamagnetic drift expected to occur with any denstity gradient the driving mechanism for the drift waves is the presence of the density gradient perpendicular to the ambient magnetic field vector. They are NOT fluid drifts!
==> No driver is needed to excite the drift waves, unlike for MHD waves!

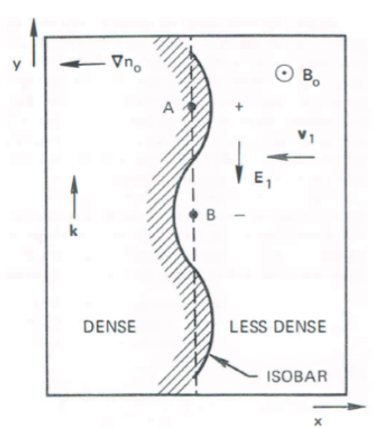


There are ample examples of observed inhomogeneities in the solar atmosphere!!!
==> plenty of sources to excite drift waves

Typical geometry of the drift waves:

* Very short wavelength along ***B***, long wavelength along ***B***
* Figure shows *n* and *ϕ* perturbation.
* According to linear theory, the driving mechanism depends on the existence of a phase difference between the wave electric field (or potential) and the plasma density oscillations
*** Requires separate dynamics for ions and electrons**
==> MHD approach commonly used to model the solar corona do not describe drift waves!





Collisional drift wave instability:

* Without resistivity: radial ExB drift and ion density fluctuations are 90° out of phase, perturbation propagates perpendicular to div (n) --> no radial transport
* With resistivity: delay in the electron response, which causes a lag in the phase of *ϕ* with respect to *n* --> drift waves instability and transport
* Electron collisions always cause drift waves to grow

Developing a model to study drift waves

Goal: to develop a multi-fluid model to simulate drift waves in the solar atmospheric plasma, due to density inhomogeneities

We use the COOLFluid platform - Component-based, open source, HPC platform for fluid dynamics, plasma and multiphysics simulations
- http://andrealani.github.io/COOLFluiD/

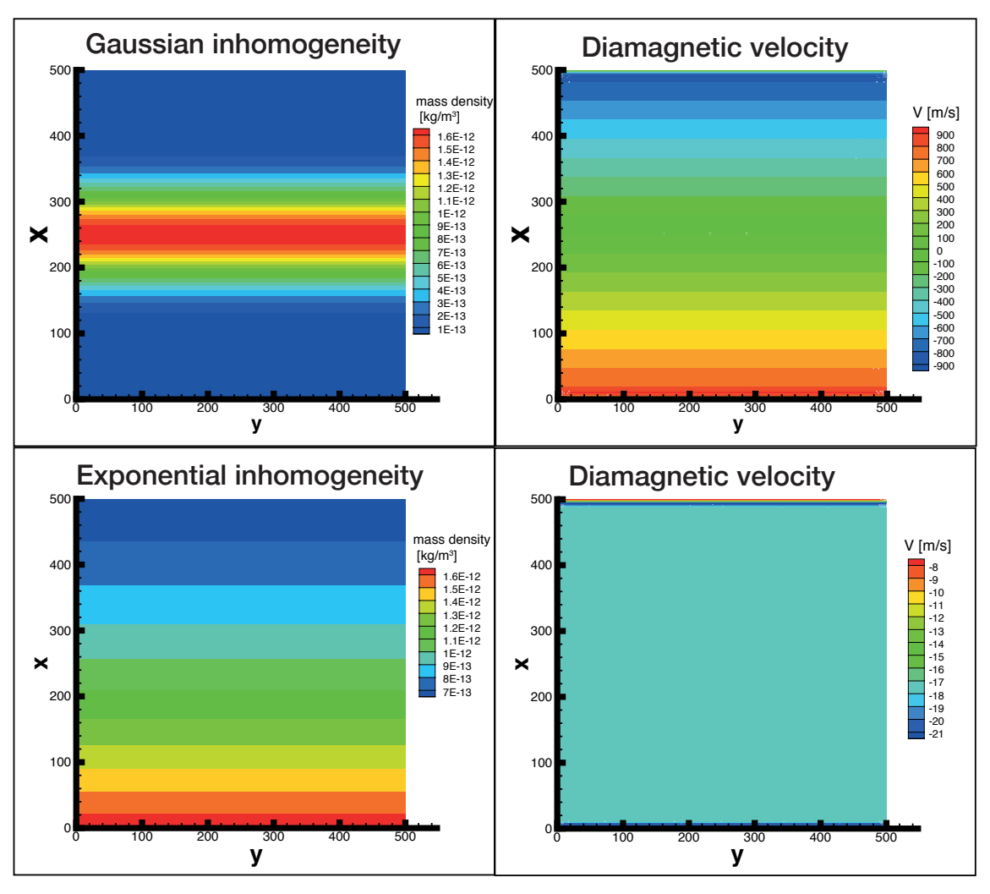
We use a Finite Volume approach to solve the fluid equations for the different species. We consider full Maxwell's equations to allow for charge separation.
We choose implicit time stepping - restricted by the stiffness of the system
AUSM+ - up methodology for multi-fluid equations (A. Laguna, et al. JCP (2015) in press)

Current status: We have developed two-fluid (electrons and ions) and multifluid (electrons, ions, and neutrals) modules in 2.5 D geometry (2 D in space and 3D in velocity space).

We expect the collisionsl drift wave to be destabilized by electron resistivity parallel to the ambient magnetic field and to be stabilized by ion viscosity in the perpendicular direction.

For our simulations we consider typical coronal values:
T = 10^6 K for ions and electrons
n = 10^{15} m^{-3}
B = 10^{-2} T

We are exploring the differences in the simulations due to the plasma density profiles



Governing equations

ion and electron momentum equations

$$m_i n_i \frac{d\,\mathbf{v}_i}{dt} = e n_i(-\nabla\phi + \mathbf{v}_i \times \mathbf{B}_0) - kT_i\nabla n_i - \nabla\cdot\pi_i - m_i n_i \nu_i \mathbf{v}_i$$

$$0 = -e n_e(-\nabla\phi + \mathbf{v}_e \times \mathbf{B}_0) - kT_e\nabla n_e - m_e n_e \nu_e\ \mathbf{v}_e$$

where
Convective derivative $\frac{d\mathbf{v}_i}{dt} = \frac{\partial\mathbf{v}_i}{\partial t} + (\mathbf{v}_i\cdot\nabla)\mathbf{v}_i$
m_i=mass of ion
n_i=number density of ions
n_e=number density of electrons
m_e=mass of electron
$\mathbf{v}_i$=velocity of ion
ϕ=scalar potential

ion and electron continuity equations

$$\frac{\partial n_i}{\partial t} + \nabla_\perp\cdot(n_i v_{i\perp}) + \nabla_z\cdot(n_i v_{iz}) = 0$$

$$\frac{\partial n_e}{\partial t} + \nabla_\perp\cdot(n_e v_{e\perp}) + \nabla_z\cdot(n_e v_{ez}) = 0$$

diamagnetic frequency of electrons and ions

$$\omega_{di} = -k_y \frac{v_{ti}^2}{\Omega_i}\frac{n_{i0}'}{n_{i0}} \qquad \omega_{de} = -k_y \frac{v_{te}^2}{\Omega_e}\frac{n_{e0}'}{n_{e0}}$$

dispersion relation for drift waves in collisional plasma

$$\frac{T_e}{T_i}\frac{\omega_{di} + \omega\rho_i^2 k_y^2(1+\frac{1}{2}\rho_i^2 k_y^2) + i\nu_i\rho_i^2 k_y^2}{\omega[1+\rho_i^2 k_y^2(1+\frac{1}{2}\rho_i^2 k_y^2)] + i\nu_i\rho_i^2 k_y^2} + \frac{\omega_{de} + i(D_p+D_z)}{\omega + i(D_p+D_z)} = 0$$

$$D_p = \nu_e k_y^2 \rho_e^2 \text{ and } D_z = k_z^2 v_{te}^2/\nu_e$$

kinetic approach

$$\omega_r = -\frac{\omega_{*i}\Lambda_0(b_i)}{1-\Lambda_0(b_i)+T_i/T_e+k_y^2\lambda_{di}^2}, \qquad \frac{\omega_r-\omega_{*e}}{|k_z|v_{Te}}\exp\left[-\omega_r^2/(k_z^2 v_{Te}^2)\right]$$

$$\Lambda_0(b_i) = I_0(b_i)\exp(-b_i), \quad b_i = k_y^2\rho_i^2, \quad \lambda_{di} = v_{Ti}/\omega_{pi},$$

$$+\frac{\omega_r-\omega_{*i}}{|k_z|v_{Ti}}\exp\left[-\omega_r^2/(k_z^2 v_{Ti}^2)\right]\Big\}.$$

fluid approach

$$K\omega_r + G\omega_r^2 - G\omega_i^2 + L - M\omega_i + i(K\omega_i + 2G\omega_r\omega_i + N + M\omega_r) = 0$$

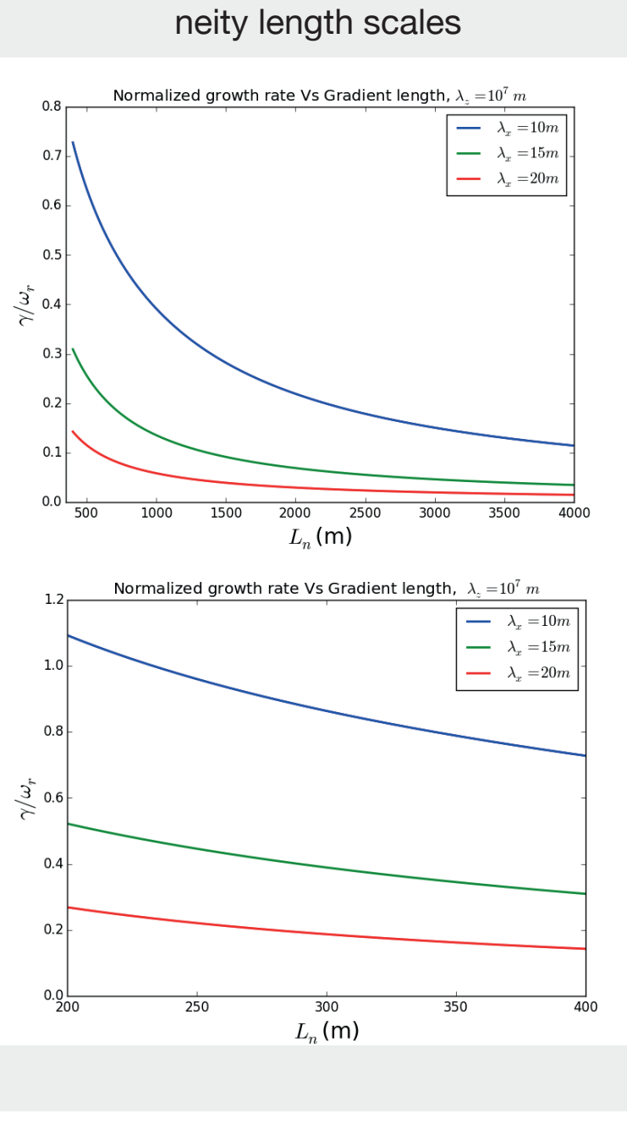
where
K=F+I, L=H+J, M=B+C+D, N=A+E.
where
$A = \frac{T_e}{T_i}(\omega_{di}(D_p+D_z))$
$B = \frac{T_e}{T_i}\rho_i^2 k_y^2(D_p+D_z)(1+\frac{1}{2}\rho_i^2 k_y^2)$
$C = \frac{T_e}{T_i}\nu_i\rho_i^2 k_y^2$
$D = (1+\rho_i^2 k_y^2(1+\frac{1}{2}\rho_i^2 k_y^2))(D_p+D_z)$
$E = \nu_i(\omega_{de})\rho_i^2 k_y^2$
$F = \frac{T_e}{T_i}\omega_{di}$
$G = \frac{T_e}{T_i}\rho_i^2 k_y^2(1+\frac{1}{2}\rho_i^2 k_y^2)$
$H = -\frac{T_e}{T_i}\nu_i\rho_i^2 k_y^2(D_p+D_z)$
$I = \omega_{de}(1+\rho_i^2 k_y^2(1+\frac{1}{2}\rho_i^2 k_y^2))$
$J = -\nu_i\rho_i^2 k_y^2(D_p+D_z)$

$$K\omega_r + G\omega_r^2 - G\omega_i^2 + L - M\omega_i = 0$$

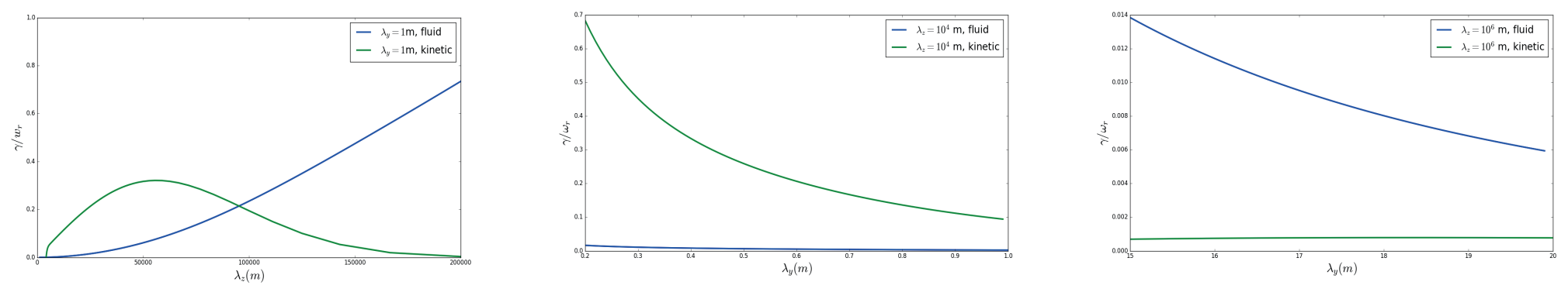
$$K\omega_i + 2G\omega_r\omega_i + N + M\omega_r = 0$$

$$\omega_i = \frac{-N - M\omega_r}{K = 2G\omega_r}$$

Normalized growth rates for drift waves in two-fluid approach with different inhomogeneity length scales



Comparison of the growth rate between fluid and kinetic approx



Summary and future development:

* We propose drift waves as a candidate for explaining the solar corona heating. They are a great candidate as they only need the presence of inhomogeneities in the plasma density, which are present everywhere in the solar atmosphere. This means also that no driver is requiered to generate drift waves.
* The growth rate of the drift waves should lead to stochastic heating of the plasma, providing heating rates large enough for coronal heating
* We are developing a 3 D multifluid approach to simulate the drift waves. This model includes electrons, ions and neutrals as species, which are considered as separate fluids. Collisions are also included in the model.

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Acknowledgements:
We would like to thank A. Lani for his help with the development of COOLFluiD and its modules
These results were obtained in the framework of the projects GOA/2015-014 (KU Leuven), G.0A23.16N (FWO-Vlaanderen) and C 90347 (ESA Prodex).
This research has been funded by the Interuniversity Attraction Poles Programme initiated by the Belgian Science Policy Office (IAP P7/08 CHARM).
For the computations we used the infrastructure of the VSC – Flemish Supercomputer Center, funded by the Hercules foundation and the Flemish Government – department EWI.