Magnetic Flux Rope Models and the Effects of Coronal Density Stratification

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1. Magnetic Flux Ropes

Magnetic flux ropes are twisted bundles of magnetic flux in the solar corona. These structures can store enormous amounts of magnetic energy as the magnetic field becomes twisted by the motion of the solar surface, including differential rotation and supergranulation.

If the conditions are correct, this energy can be released very rapidly in an eruption. This process is one of the main mechanisms behind large coronal mass ejections (CMEs).

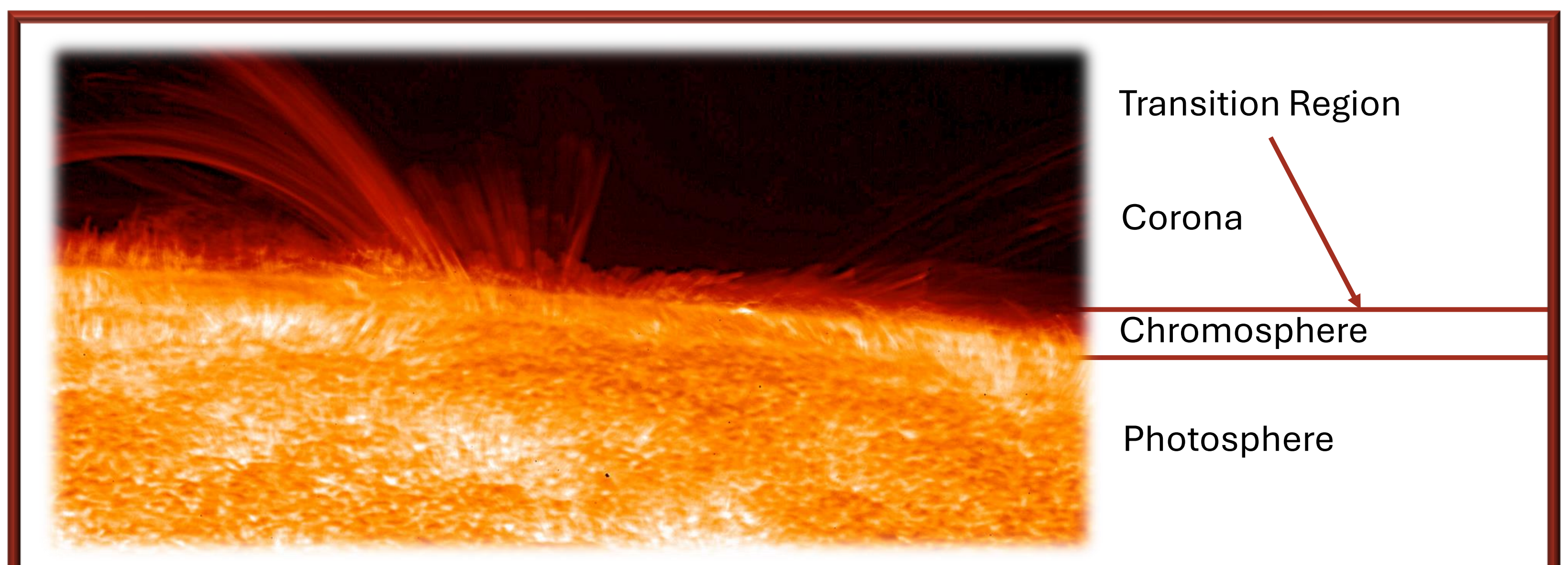

Figure 1: Image of the solar surface, with the dense photosphere, less dense chromosphere and the much less dense corona[1].

3. Predicting Flux Rope Eruptions Using Diagnostic Quantities

In previous work, we have shown that magnetofriction approximates MHD well enough **when the plasma beta is low** that we can make predictions of imminent flux rope eruptions using either model.

This was achieved using a large parameter study in 2.5D: a compromise between accuracy and speed.

We found that there are several ratios between theoretically measurable quantities which reach a threshold above which an eruption is almost certain.

These include a modification to the 'eruptivity index'[4], and various measures of the magnetic flux in the rope normalised by the helicity.[5]

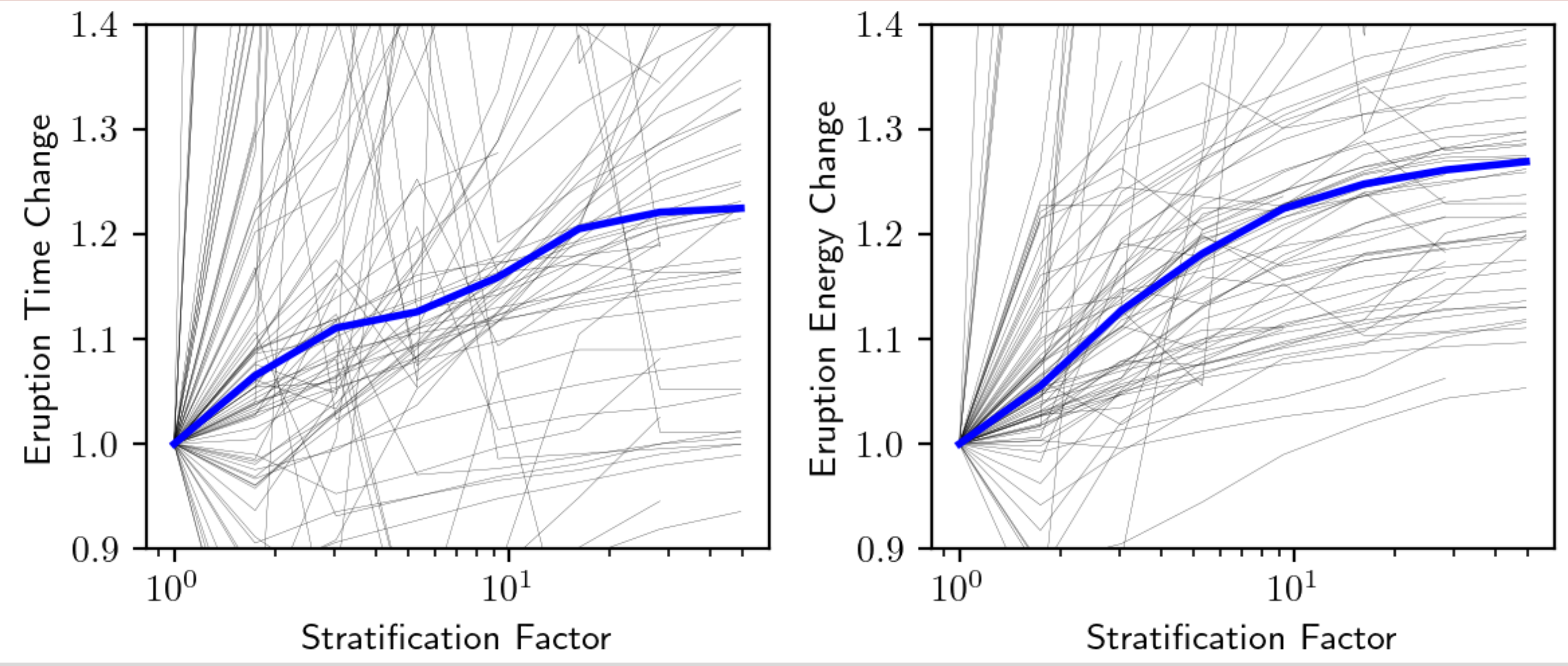

Figure 3: Relative times and energy release in flux rope eruptions, with increasing stratification factors. The median values are shown in blue.

5. (Some of) the Effects of Stratification

By running a parameter study with varying lower boundary effects, we observe the effect this has on a range of eruptions.

On average eruptions are delayed relative to no stratification (**Figure 3**), and also release more magnetic energy per eruption.

As expected, **Figure 4** shows that the Lorentz Force ($\boldsymbol{j} \times \boldsymbol{B}$) is generally higher in the stratified cases, even at altitudes significantly higher than the particularly dense boundary region.

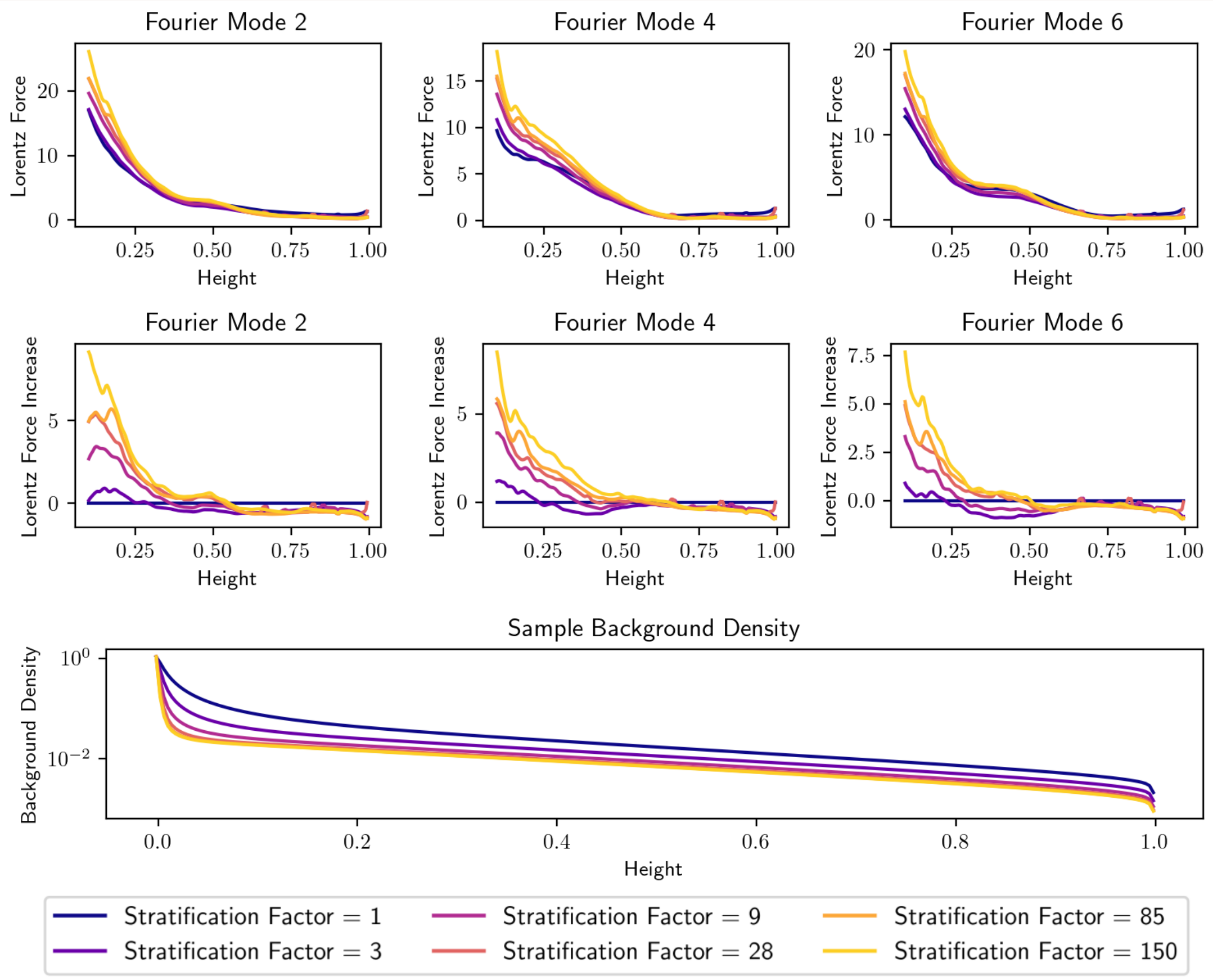

Figure 4: Fourier transforms of the Lorentz force with altitude, showing the increases due to increased stratification, along with the background density profile in each case.

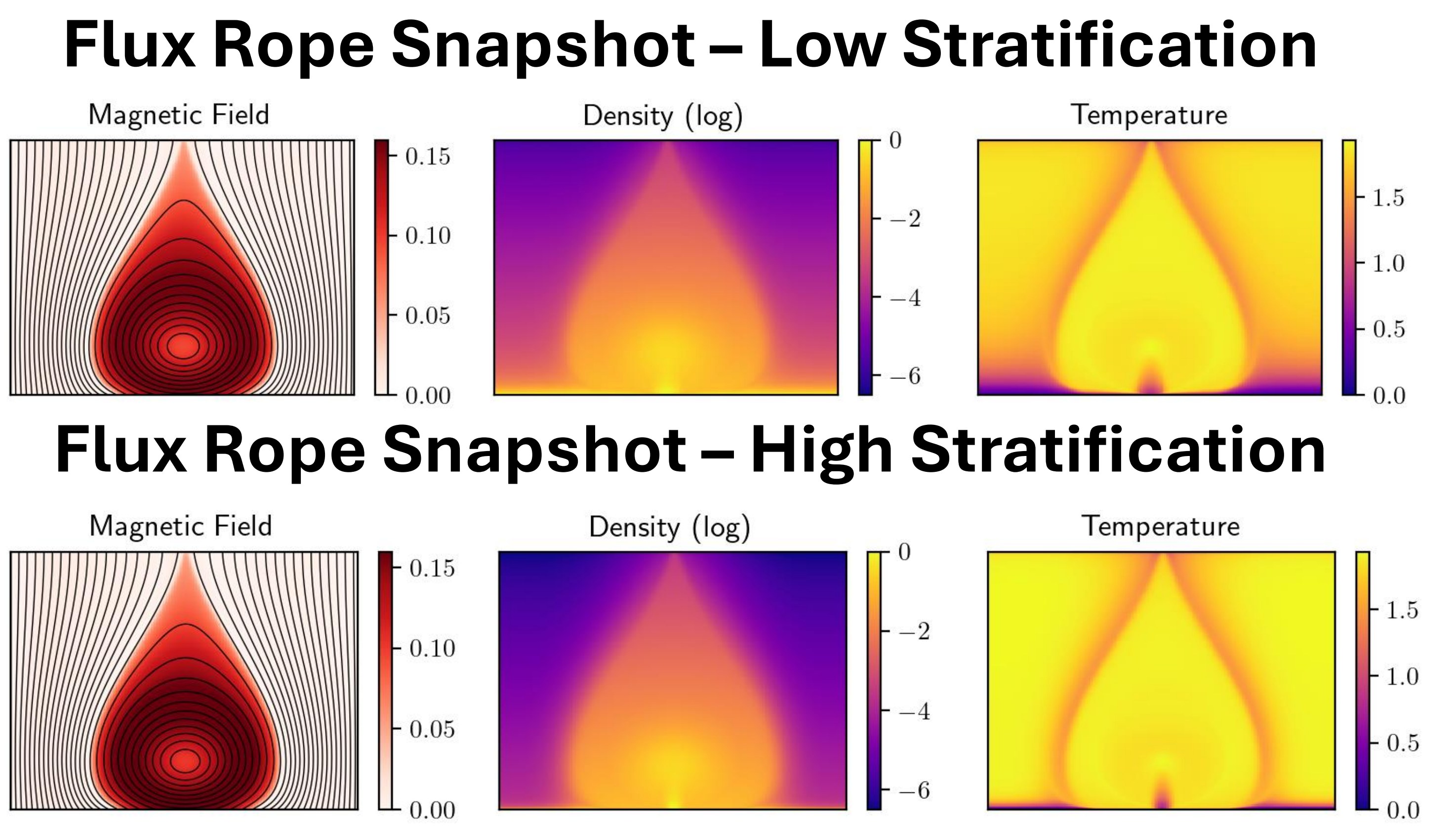

Figure 2: Snapshots of a magnetic flux rope soon after formation, showing the slight differences between low and high stratification cases.

2. Modelling Flux Rope Behaviour: MHD and Magnetofriction

Full MHD models of flux rope behaviour are possible[2] – these combine the dynamics of the magnetic field with the fluid equations to produce a physically accurate representation of magnetic field behaviour.

However, these models are still computationally slow and so we would like faster alternatives: one such alternative is magnetofriction, wherein the fluid equations are replaced by a closed form for the 'velocity'.[3]

Magnetofriction assumes the system always relaxes to a state with a low Lorentz Force. This is a decent approximation throughout most of the corona and it mimics our 'unstratified' MHD simulations well.

However, this is not necessarily true near the lower boundary, below the transition region (**Figure 1**) where the density is higher, as is modelled in our 'stratified' simulations. In our current work we seek to improve on this.

Magnetofriction Modification:

The Magnetofrictional 'Velocity'

$$\boldsymbol{v} = \frac{v_0 \boldsymbol{j} \times \boldsymbol{B}}{B^2 + \delta e^{-\delta B^2}} + v_{out}(y)\mathbf{e}_y$$

leads to equilibrium with

$$\boldsymbol{j} = \alpha \boldsymbol{B}.$$

We can subtract a 'Pressure Current' :

$$\boldsymbol{j}_p = \nabla \times \left(f(y) B_y \boldsymbol{e}_y\right)$$

such that the system is in equilibrium when

$$\boldsymbol{j} = \alpha \boldsymbol{B} + \nabla \times \left(f(y) B_y \boldsymbol{e}_y\right),$$

modelling the forces low in the corona.

4. Incorporating Coronal Stratification

In our current work we are seeking to improve upon models like these, which use boundary driving to create the magnetic structure.

Generally, such models are informed using magnetic field data from the photosphere. Above this layer lies the chromosphere, where the plasma is still relatively dense. This difference can be seen in **Figure 2**.

Hence the force-free, low-beta assumptions we often are not as valid here. This dense layer is thin but incorporating it can have a big effect!

In MHD, we incorporate this effect by modifying the method of **[6]**, essentially enforcing a cooler boundary layer in the chromosphere. This results in a different fluid density profile as seen in **Figures 2 and 4**.

6. Can this be Approximated with Magnetofriction?

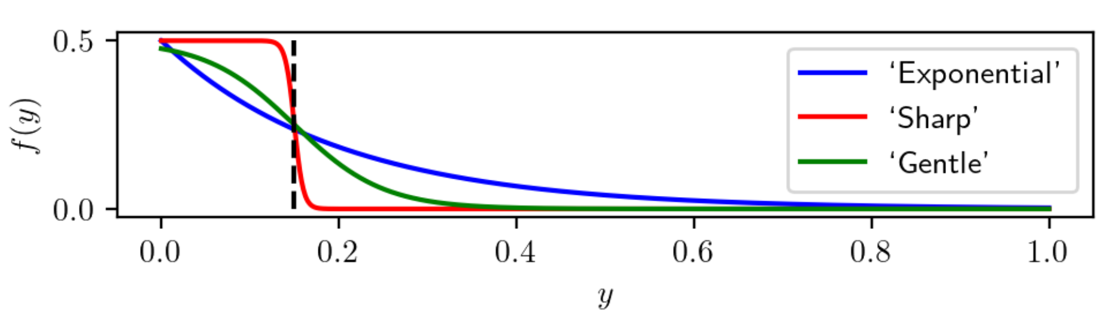

Figure 5: Three options for the 'pressure function' f(y).

If these effects are indeed significant, it would be desirable to modify the magnetofrictional model to incorporate them. This would allow for more accurate global simulations of coronal behaviour.

One solution is to add a 'pressure' term to encourage the Lorentz force to be higher low in the corona, motivated by the static force-free extrapolations of **[7]**.

We find that the form of the pressure function f(z) (**Figure 5**) makes a big difference.

A 'sharp' tanh profile delays eruptions nicely but produces unrealistic Lorentz force distribution, whereas an exponential decay matches the MHD simulations better but does not delay eruptions!

A compromise of a 'gentle' profile seems to be a promising compromise, with some delay and a reasonably realistic field configuration.

References

[1] 'Fine Scale Structure of the Chromosphere' - Hinode
[2] Arber et al. 2001, Journal of Computational Physics, 171, 151
[3] Craig, I.J.D. & Sneyd, D. ApJ, 311, 451
[4] Pariat, E., Leake, J. E., Valori, G., et al. 2017, A&A, 601, A125
[5] Rice, O. E. K., & Yeates, 2023, ApJ, 955, 144
[6] Prior & McTaggart, 2021, Geophysical and Astronomical Fluid Dynamics, 115, 1
[7] Neukirch & Wiegelmann, 2019, Solar Physics, 294, 12