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Simulation of sunspots in the chromosphere

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Abstract

Sunspots are one of the most prominent features of the solar surface and are characterized by a dark central core called the umbra, which is surrounded by a collection of filamentary structures called the penumbra. The penumbra is on average considerably brighter than the umbra but darker than the surrounding quiet Sun. At the photospheric level, the nearly horizontal Evershed flow is directed outward from the outer edge of the umbra along penumbral filaments. On the other hand, in the chromosphere, the flow is reversed and the plasma flows inwards towards the umbra. Radiative magneto-hydrodynamic (rMHD) codes have simulated sunspots in the upper convection zone and photosphere (Heinemann et al., 2007; Rempel, 2009). Models of sunspots that include a realistic treatment of the chromosphere and corona have not yet been performed. However, strong magnetic field regions such as sunspots and active regions are the location at which the initiation of solar flares and other eruptive phenomena that drive space weather occurs. The structure and evolution of the chromospheric field will be important in understanding magnetic reconnection and processes that are important for flare initiation. In this poster, we will present preliminary simulations that extend the previous simulations higher into the solar atmosphere.

Simulation Setup and Methods

As a starting point, a **hydrodynamic (HD) quiet Sun** region with no magnetic field was simulated in a 3D slab setup using the **MURaM rMHD** code [6][4].

- **Domain size**: 36 Mm × 6 Mm × 10.302 Mm
- **Vertical extent**: 9.802 Mm below and 0.5 Mm above the average solar surface
- **Resolution**: 48 km (horizontal), 17 km (vertical)

After convection fully developed, a **magnetic flux tube** was inserted and the simulation was run until a stable sunspot formed. **Extension of the box** to higher layers was achieved by performing a potential field extrapolation of the magnetic field.

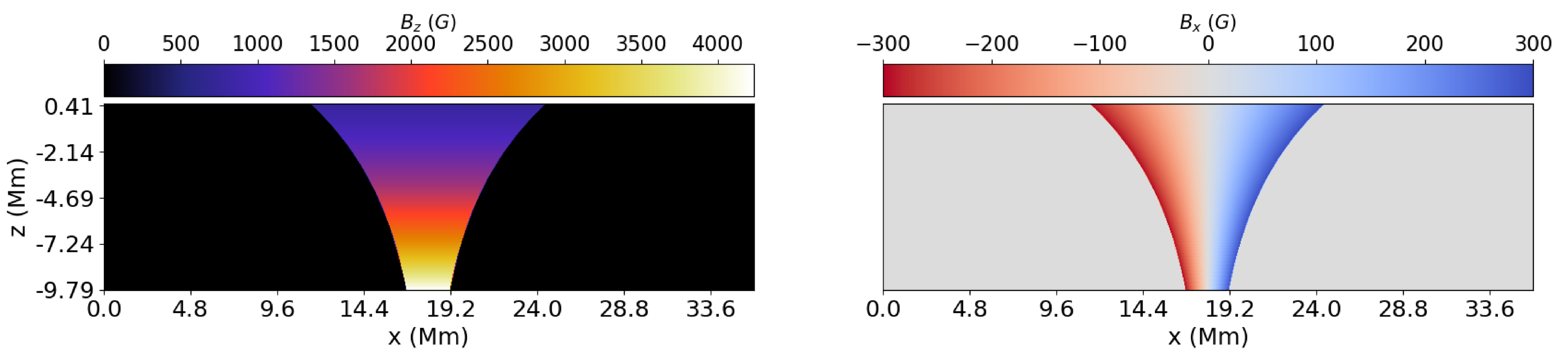

Figure 1. B_z and B_x profile of the initial flux tube

Structure at the Photosphere

Sunspots are of varied size and structure, hosting a diverse range of phenomena including the light-bridges, umbral dots, penumbral fine structure, and prominent Evershed flow which is the radial outflow of plasma from the umbra.

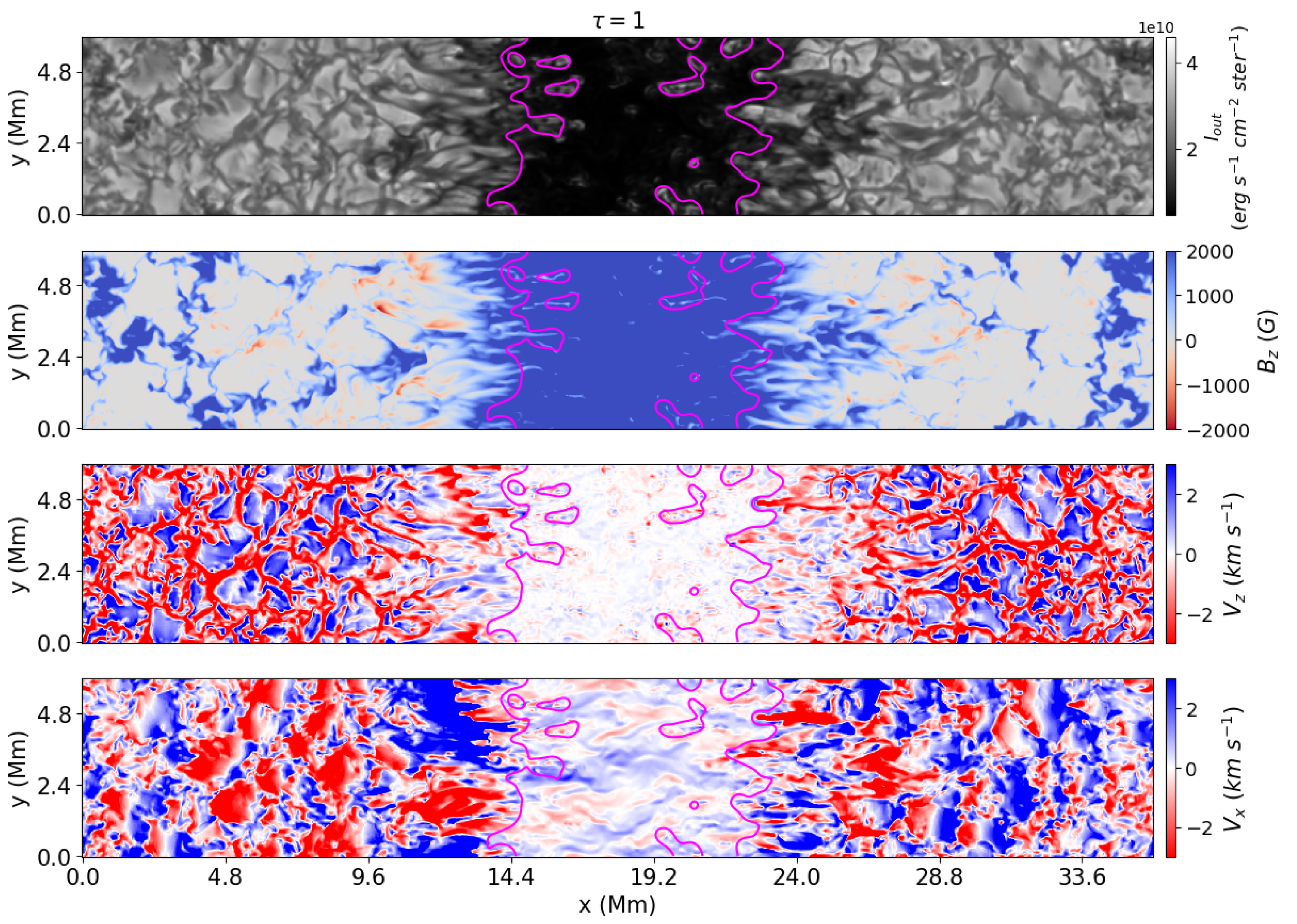

Figure 2. Optical depth (τ) = 1 surface showing intensity, magnetic and velocity field. The magenta contour (40% of quiet sun intensity) marks the umbral boundary. The colorbars are saturated, the velocities can reach up to 6 km/s and higher in certain regions. The B_z values at the umbra can reach up to 5 kG.

Twinspot

A twinspot configuration helps us reduce the impact of the top boundary condition (half open, where no inflows are allowed) on our simulation by creating loops through which plasma flow can be contained in the simulation box. Enhancing the flux at the edges of the initial flux tube aids in penumbra formation.

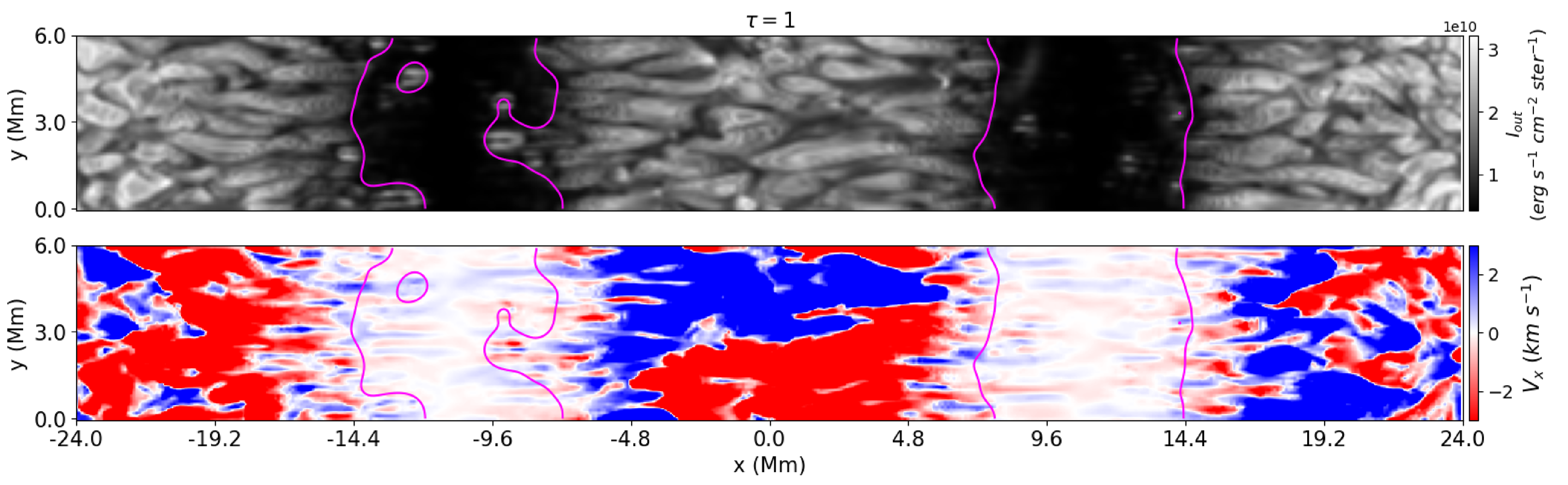

Figure 3. Horizontal slice through the photosphere. The top panel shows the Intensity map and the bottom panel shows the horizontal velocity (V_x) map. The magenta contour defines the umbral boundary. The colorbar is saturated, the velocities can reach up to 6 km/s and higher in certain regions.

Inverse Evershed Flow

- Focus: **Inverse Evershed Flow** (IEF) — inward plasma flow toward the umbra in the chromosphere and transition region.
- **Siphon flow** is a likely driver [1], but lacks self-consistent modeling to explain IEF formation.
- **Observations**: limited by resolution and challenges in tracing 3D magnetic field structures.
- **Goal**: Investigate driving mechanisms and properties of IEF channels in sunspot chromosphere.

Sunspot in the Chromosphere

The filamentary features visible on either side of the umbra in the chromosphere are ubiquitous. The flow direction in V_x and V_z shows an inward motion from beyond the penumbra toward the umbra. To obtain clearly defined superpenumbral filaments, the boundary condition will be modified.

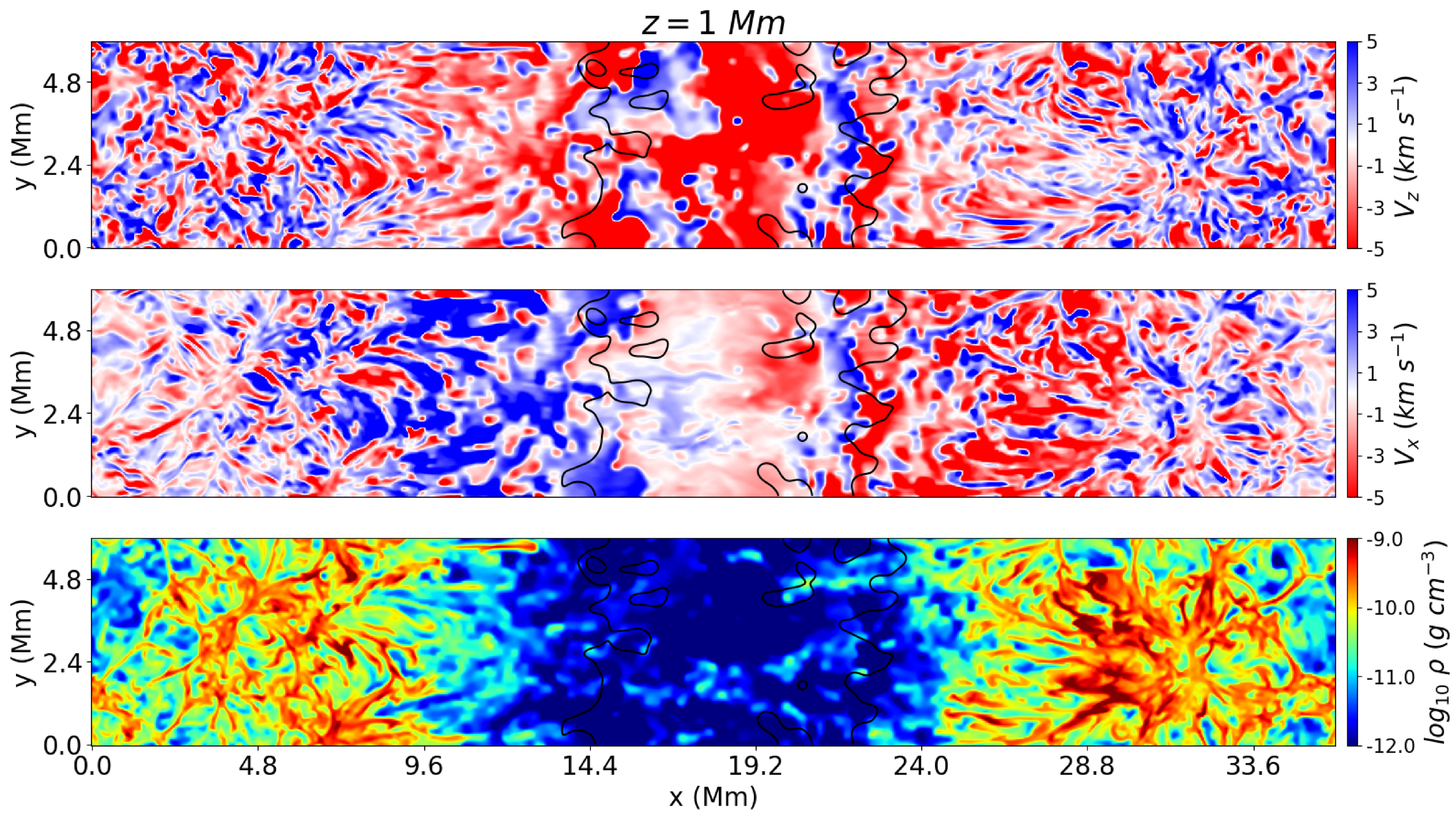

Figure 4. Horizontal slice through the low chromosphere, 1 Mm above the solar surface. The panels show, top to bottom: vertical component of velocity, horizontal component of velocity, and the density. The black contour (40% of quiet sun intensity) marks the umbral boundary. The colorbars are saturated, the velocities can reach up to 15 km/s and higher in certain regions.

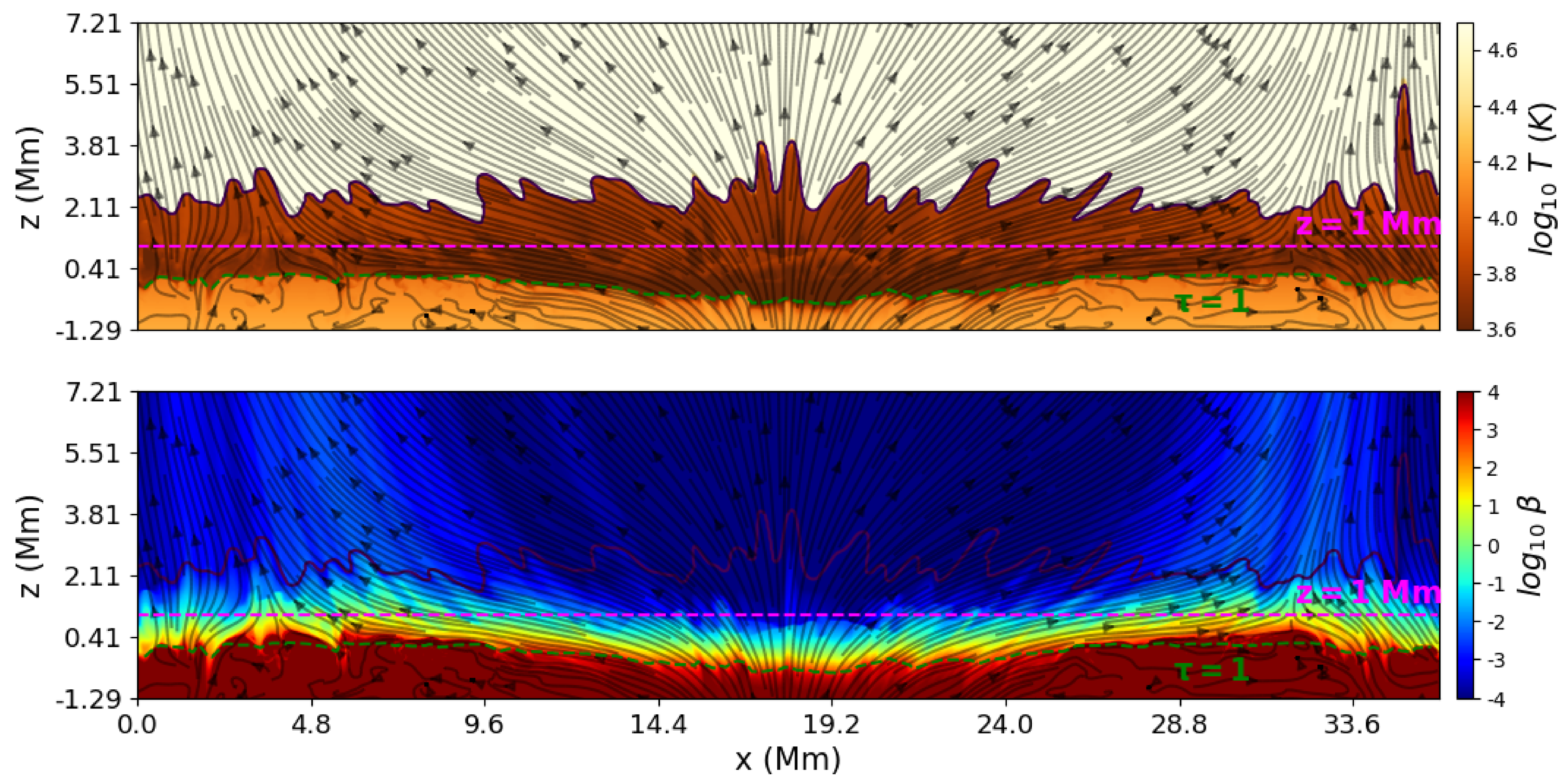

Figure 5. Vertical slice at y = 3 Mm, showing the upper convection zone, photosphere and atmosphere above the sunspot. The panels show, top to bottom; the temperature, and the plasma beta. The magnetic field lines are seen in black.

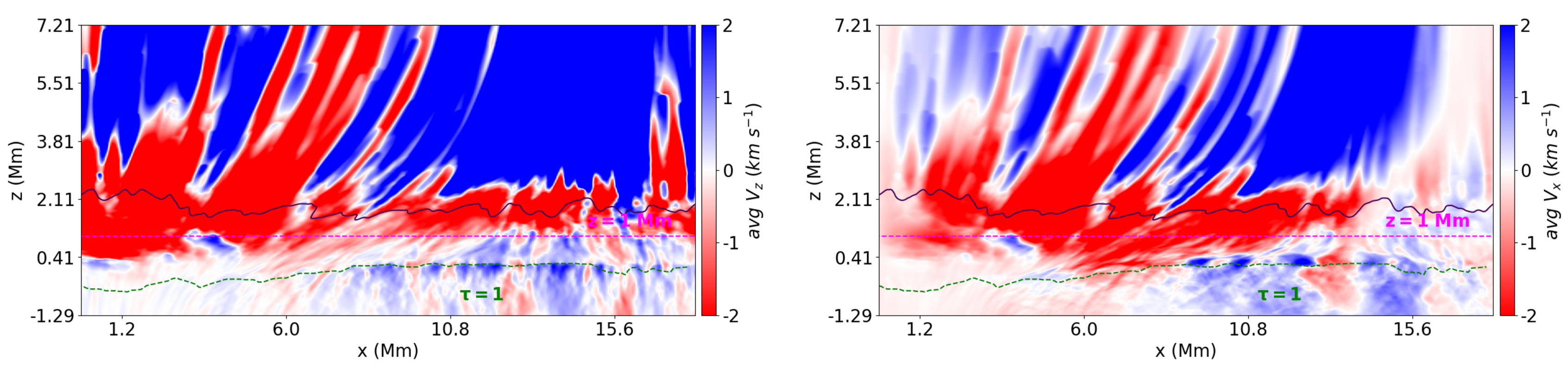

Figure 6. V_z and V_y vertical slices showing the flow structure averaged over y-direction and 30 minutes in time. The colorbars are saturated, the $avg\ V_z$ and $avg\ V_x$ values can reach above 40 km/s and 10 km/s respectively in the higher layers.

Conclusion & Future Direction

The umbra is clearly identifiable in the vertical velocity map as a region of suppressed convection at the center of the sunspot. Key observations include:

- **Plasma motion**: The horizontal slice and the averaged vertical slices of V_z and V_x show dominant downflows directed inward toward the umbra.
- **Vertical slice through the extended atmosphere**: Fine jet-like structures are distributed throughout the domain, with plasma motion higher up closely following the magnetic field configuration.
- **Twinspot**: There are outward directed flows on either side of the umbra. The filaments appear to be well defined relative to the single spot configuration.

We will perform more sunspot configurations such as sunspot near a plage including a comprehensive set of chromospheric physics to more accurately model the chromosphere (Przybylski et al. 2022).

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