Max-Planck-Institut für Sonnensystemforschung

Magnetohydrostatic modelling of the solar atmosphere: Test and application

Xiaoshuai Zhu (朱小帅, zhu@mps.mpg.de) & Thomas Wiegelmann

Max-Planck-Institute for Solar System Research, Goettingen, Germany

EGU2020 Sharing Geoscience Online, 07 May 2020

Outline

- **The magnetohydrostatic (MHS) extrapolation**
- Test with a Low’s special MHS solution
- Test with a radiative MHD simulation
- Apply to a SUNRISE/IMaX vector magnetogram
- Summary

MHS extrapolation: Extrapolations overview

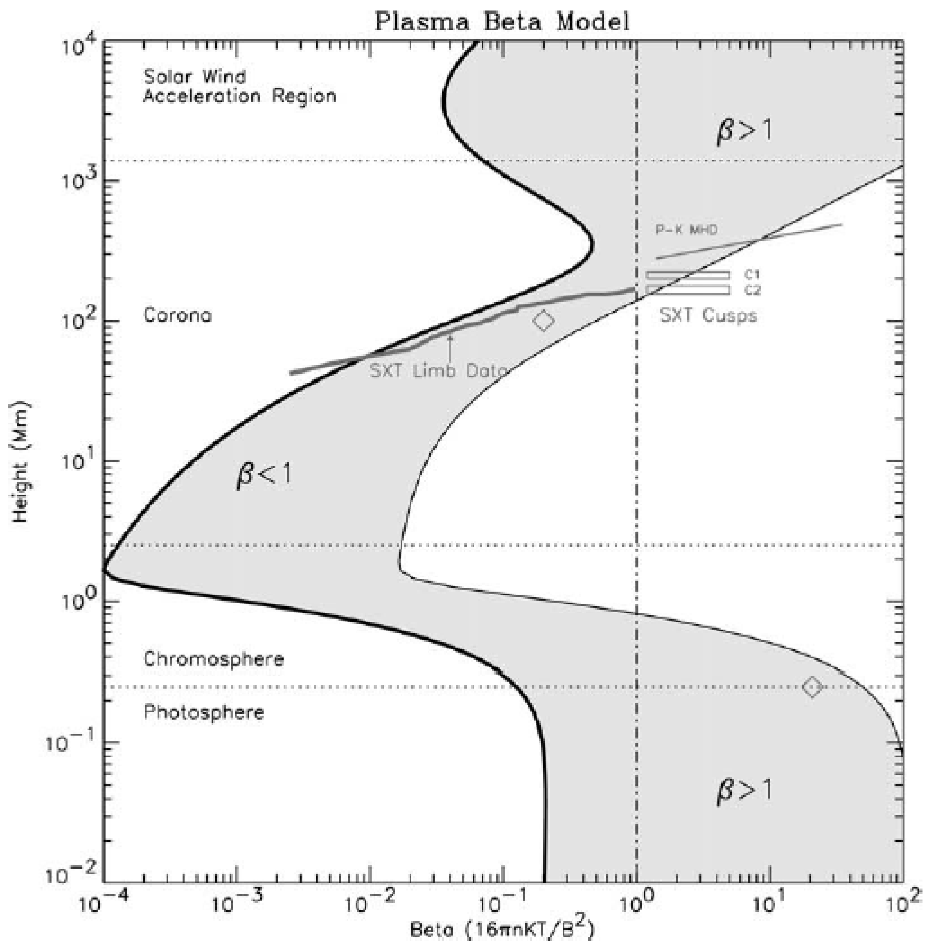


Figure 3. Plasma beta model over an active region. The plasma beta as a function of height is shown shaded for open and closed field lines originating between a sunspot of 2500 G and a plage region of 150 G. (The plage curve can also represent older, decaying active regions that have no umbral features.) The *diamond symbols* mark the photospheric and coronal example points used in the text. Various data indicate that β approaches unity at relatively low heights in the mid-corona as explained in the text.

Gary (2001)

- $\beta < 1$ in the upper chromosphere and corona: force-free field
- $\beta \geq 1$ in the lower chromosphere and photosphere: MHS state

MHS extrapolation: method

Max-Planck-Institut für Sonnensystemforschung

NLFFF optimization[2][3]

NLFFF equations: $(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = 0$

$$\nabla \cdot \boldsymbol{B} = 0$$

Functional: $L = \int_V [B^2(\Omega_a^2+\Omega_b^2)]dV$

where: $\boldsymbol{\Omega_a} = [(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}]/B^2$

$$\boldsymbol{\Omega_b} = [(\nabla \cdot \boldsymbol{B})\boldsymbol{B}]/B^2$$

Initial condition: potential field

$$minimize\ L(\boldsymbol{B})$$

MHS optimization[4][5][6]

MHS equations: $(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} - \nabla p - \rho\hat{z} = 0$

$$\nabla \cdot \boldsymbol{B} = 0$$

Functional: $L = \int_V [B^2(\Omega_a^2+\Omega_b^2)]dV$

where: $\boldsymbol{\Omega_a} = [(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} - \nabla p - \rho\hat{z}]/(B^2 + p)$

$$\boldsymbol{\Omega_b} = [(\nabla \cdot \boldsymbol{B})\boldsymbol{B}]/(B^2 + p)$$

Initial condition: NLFFF + atmosphere

$$minimize\ L(\boldsymbol{B}, p, \rho)$$

$$\boxed{\begin{array}{c} \boldsymbol{p = Q^2}, \qquad \boldsymbol{\rho = R^2} \\ \boldsymbol{minimize\ L(B, Q, R)} \end{array}}$$

MHS extrapolation

Max-Planck-Institut für Sonnensystemforschung

Bottom boundary condition for plasma:

- Pressure boundary: $p + \frac{B_z^2}{2} = p_{quiet}$, where p_{quiet} is the gas pressure in the quiet region
- Density boundary: $\rho = p/T$ (uniform temperature)

Numerical implementation

1. Calculating a NLFFF by using vector magnetogram
2. Creating a gravity stratified atmosphere based on the boundary conditions of plasma.
3. Iterating $(\vec{B}, Q, R)$ until L reaches minimum

Outline

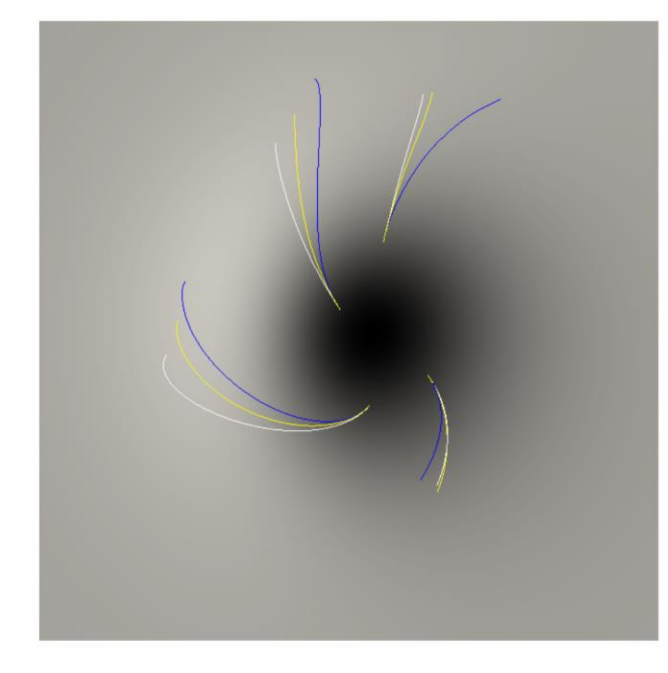
- The magnetohydrostatic (MHS) extrapolation
- **Test with a Low's special MHS solution**
- Test with a radiative MHD simulation
- Apply to a SUNRISE/IMaX vector magnetogram
- Summary

Max-Planck-Institut für Sonnensystemforschung

Test1

Max-Planck-Institut für
Sonnensystemforschung

Low's MHS solution [7] by assuming $\nabla \times B = \alpha B + f(z)\nabla B_z \times \hat{z}$, where α is a constant and $f(z) = ae^{-\kappa z}$

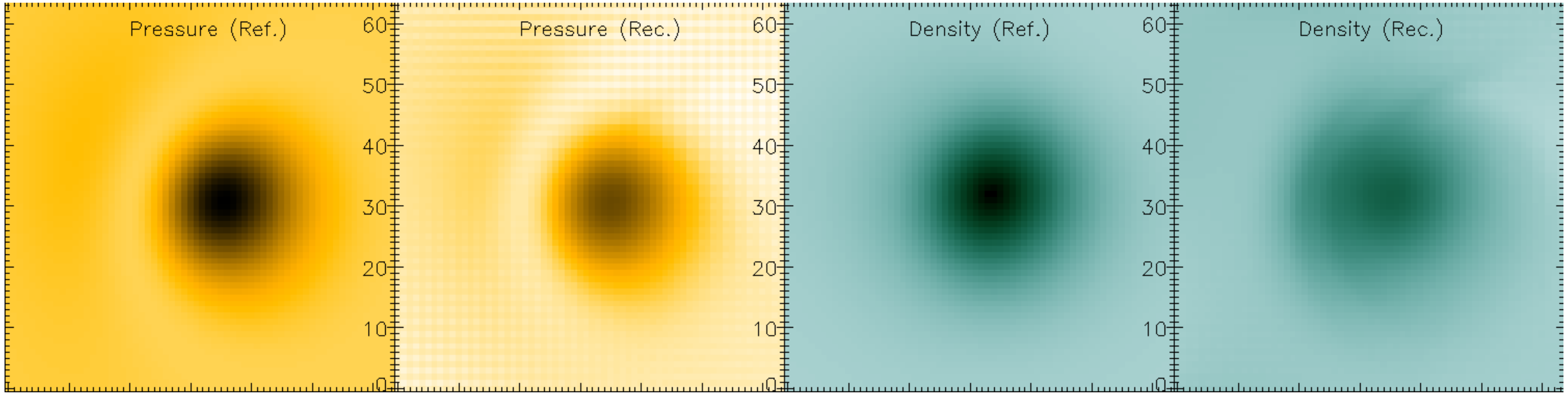


Pressure

reference | recovered

Density

reference | recovered



White: reference model

Yellow: MHS extrapolation

Blue: NLFFF extrapolation

- Reconstructed MHS field lines from our code agree with the reference solution better than NLFFF lines
- The main plasma structure is recovered by the MHS extrapolation

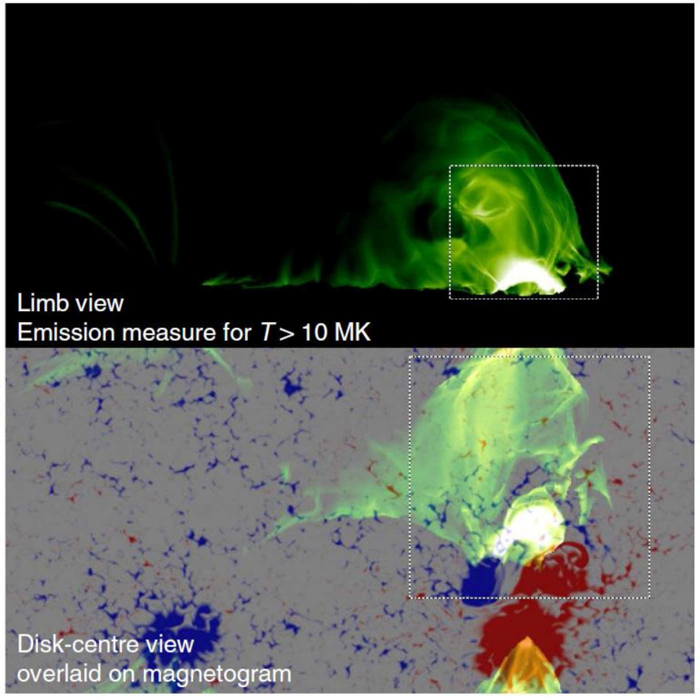
Outline

- The magnetohydrostatic (MHS) extrapolation
- Test with a Low’s special MHS solution
- **Test with a radiative MHD simulation**
- Apply to a SUNRISE/IMaX vector magnetogram
- Summary

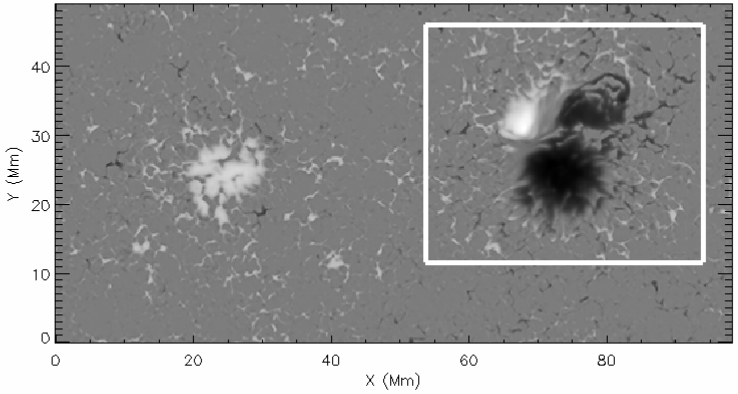
Test2: a flare simulation

Max-Planck-Institut für Sonnensystemforschung

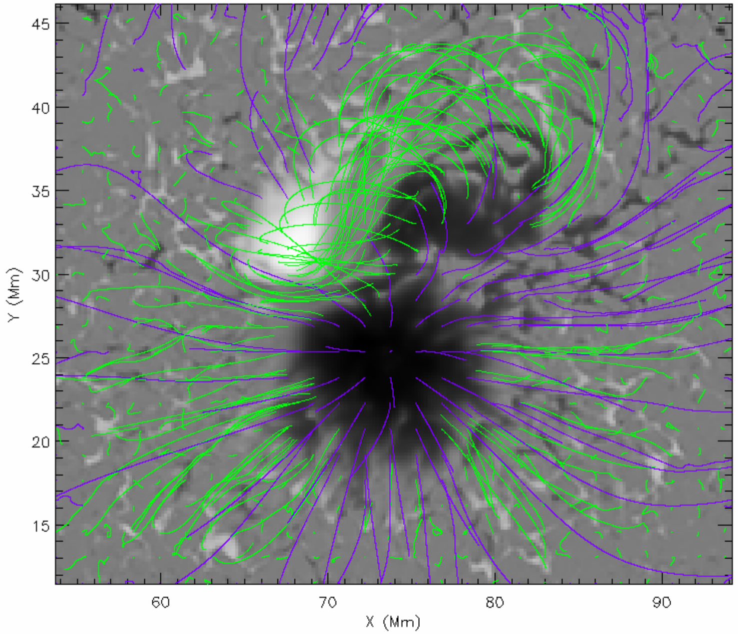
- Radiative MHD simulation [8] with MURaM code [9][10]
- snapshot selected: 8 minutes after the flare peak



Cheung et al. 2019



Selected magnetogram



Selected field lines

Test2: the plasma solution

Pressure

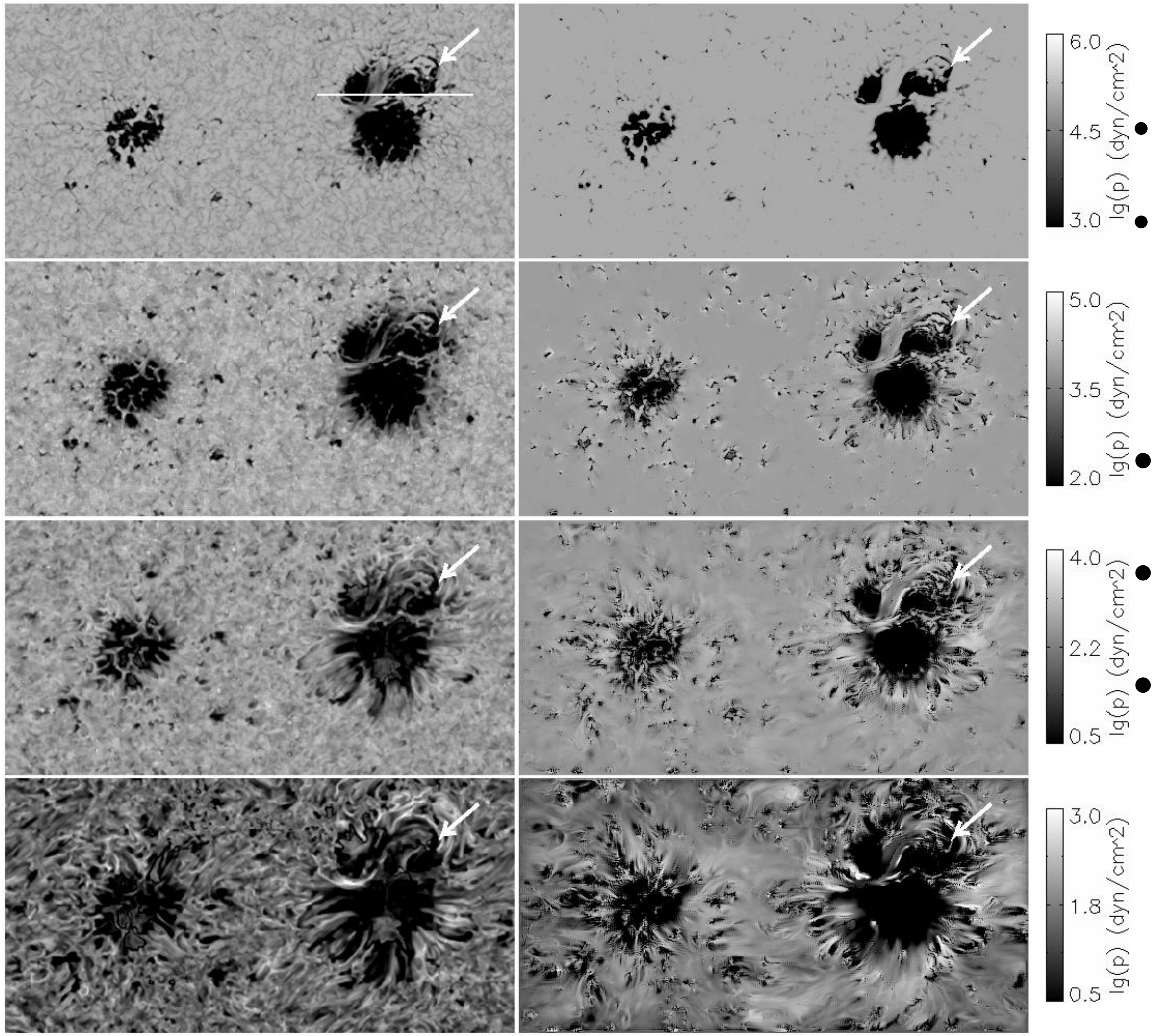
reference recovered

z=0 (Mm)

z=0.32 (Mm)

z=0.64 (Mm)

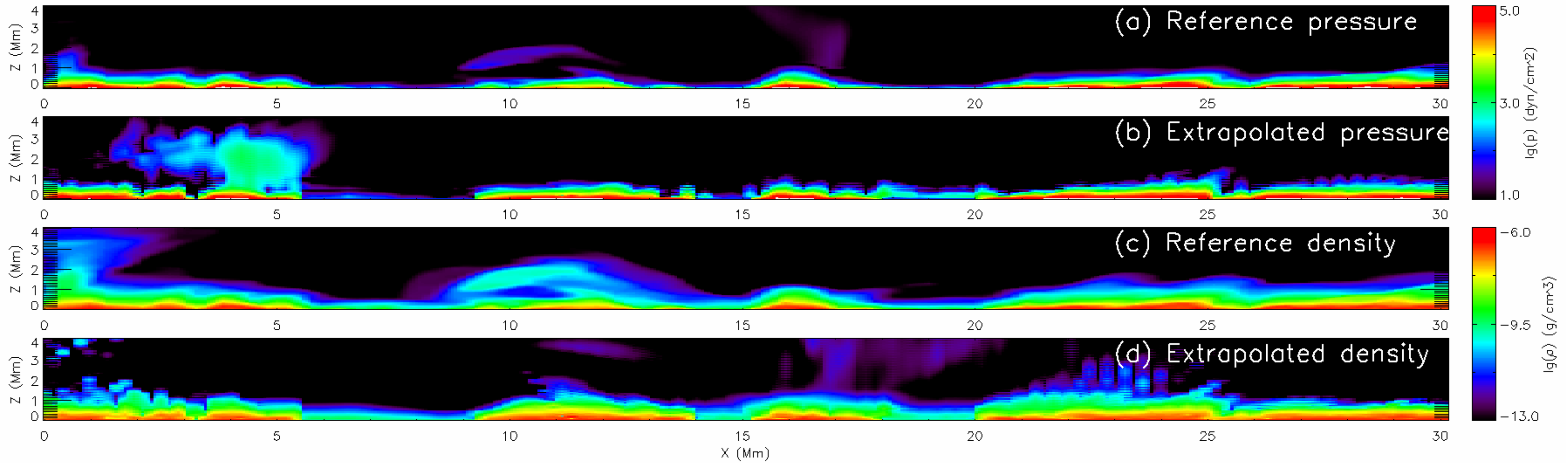
z=0.96 (Mm)



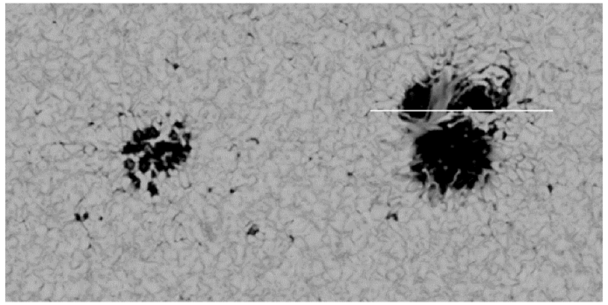
- Extrapolation dimensions: 512*256*128
- Grid spacing: 192 km transversely, 64 km vertically

- Weak pressure in the strong field region
- Spiral structure in the emerged spot
- Better reconstruction in lower layers

Test with an RMHD simulation: the plasma results

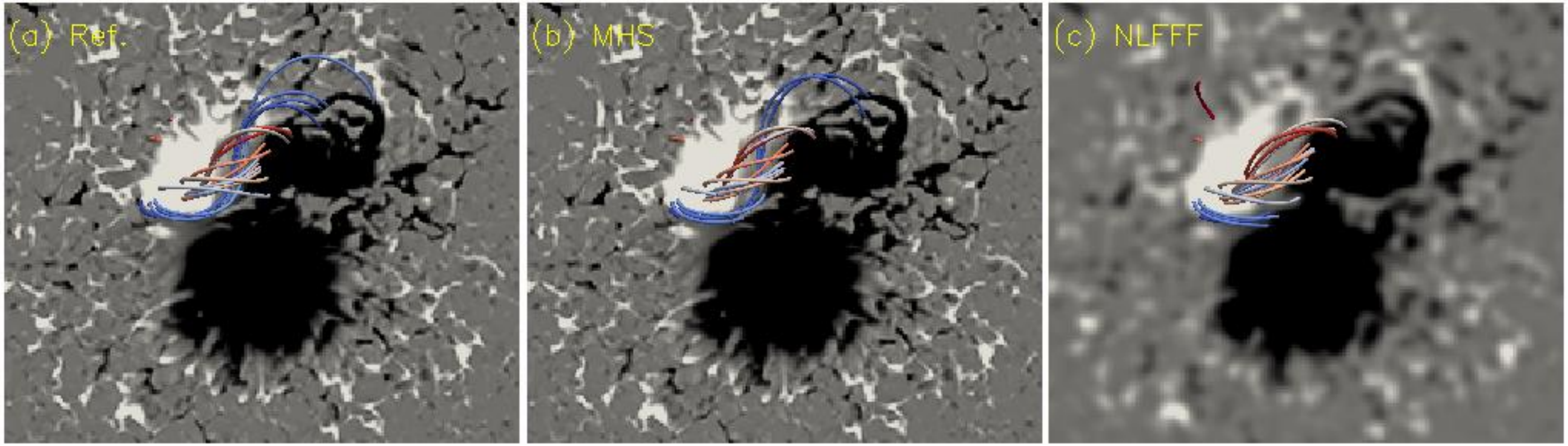


- Main plasma structures below 1 Mm can be recovered
- Above active regions the magnetic field is strong and consequently the pressure and density are low



Test with an RMHD simulation: magnetic field lines

Reference lines MHS lines NLFFF lines



- Selected field lines with the same seed points
- The twisted magnetic flux rope is well reconstructed by the MHS extrapolation
- The magnetogram for NLFFF extrapolation is preprocessed to remove the net Lorentz force and torque

Outline

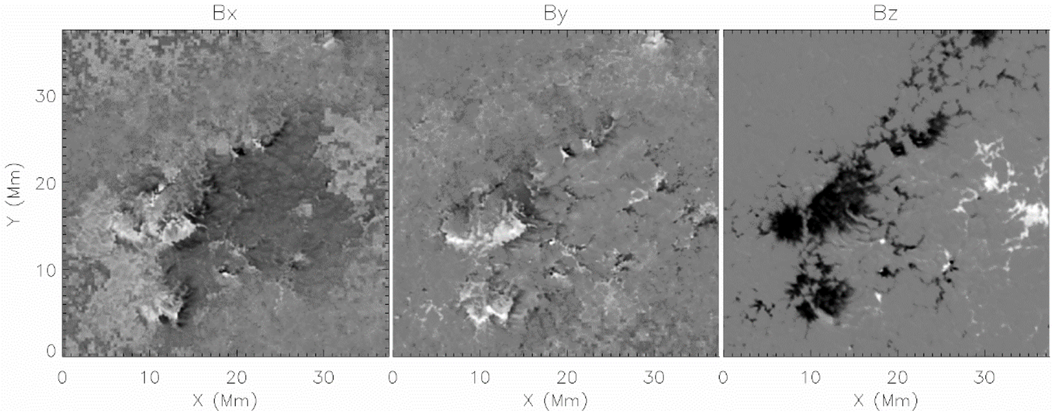
- The magnetohydrostatic (MHS) extrapolation
- Test with a Low's special MHS solution
- Test with a radiative MHD simulation
- **Apply to a SUNRISE/IMaX vector magnetogram**
- Summary

Apply to SUNRISE/IMaX: Data

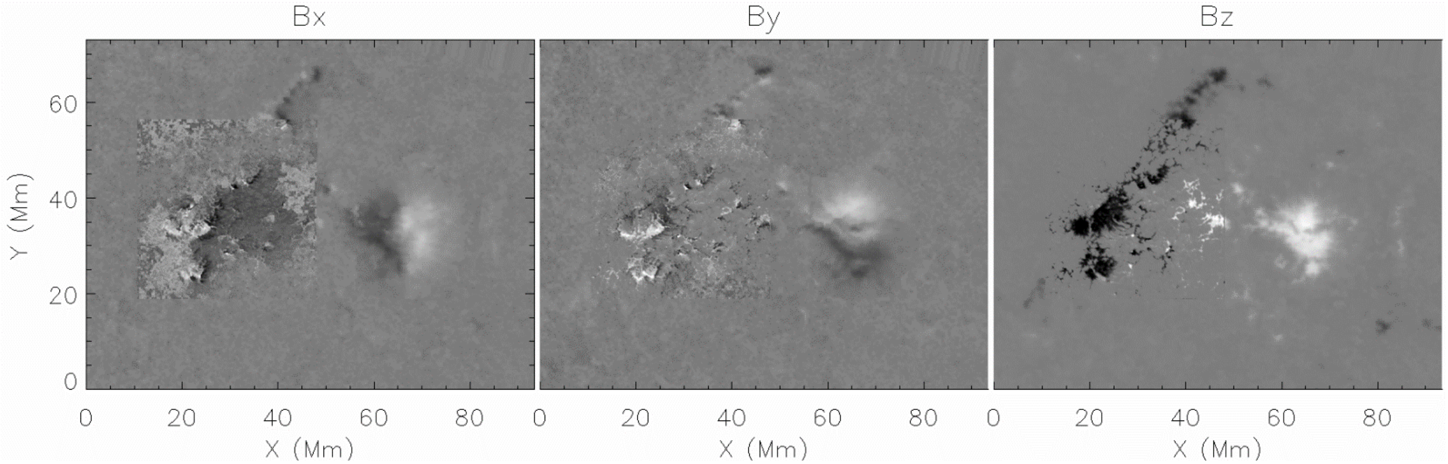
SUNRISE: A balloon-borne observatory[11]

IMaX: Spectral line: Fe I 5250.2Å, sampled at 8 wavelength positions

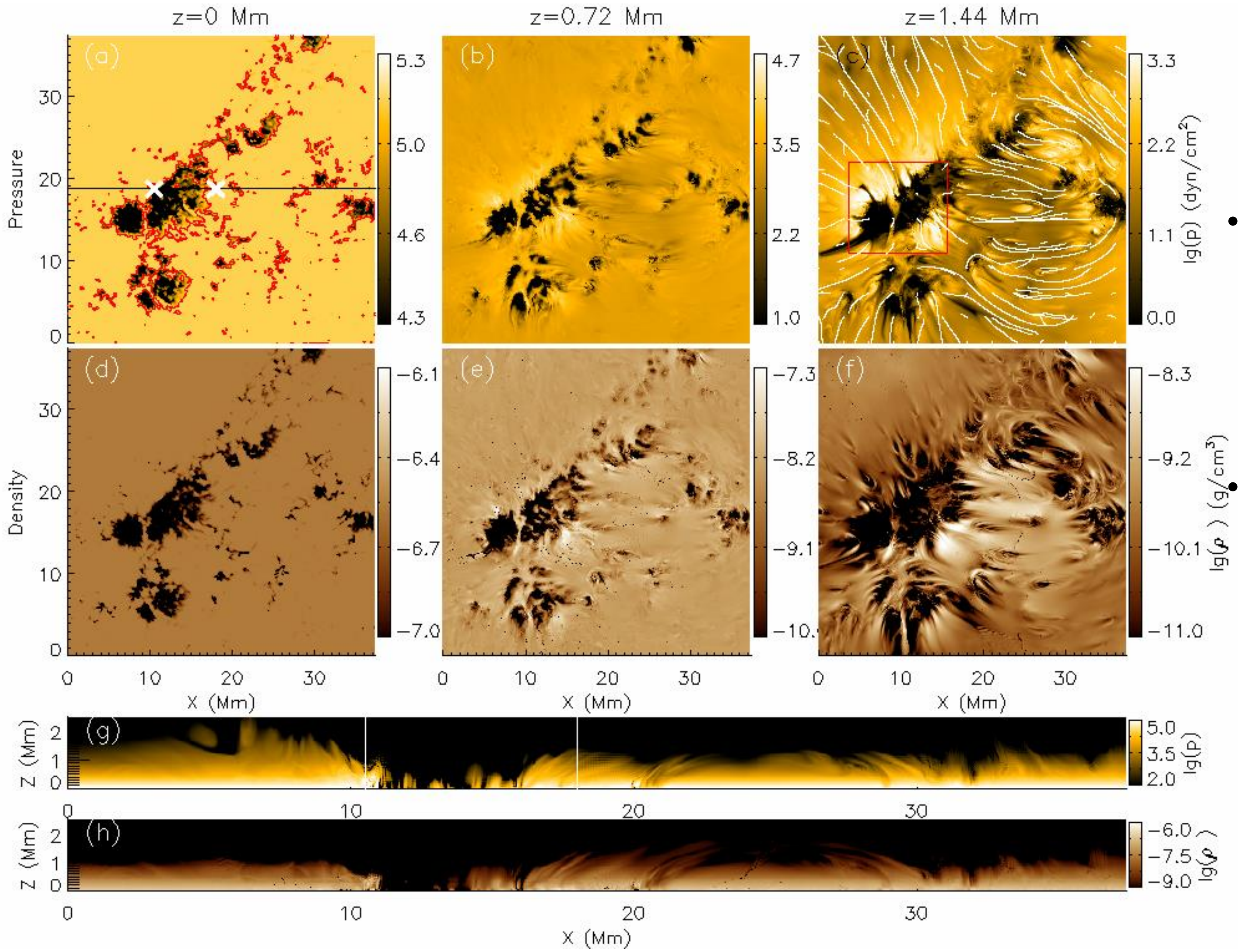
IMaX data: Scale per pixel $0''.05446 \approx 40\ km$, FOV: $936 \times 936\ pixel^2$ $(37 \times 37\ Mm^2)$



IMaX magnetogram

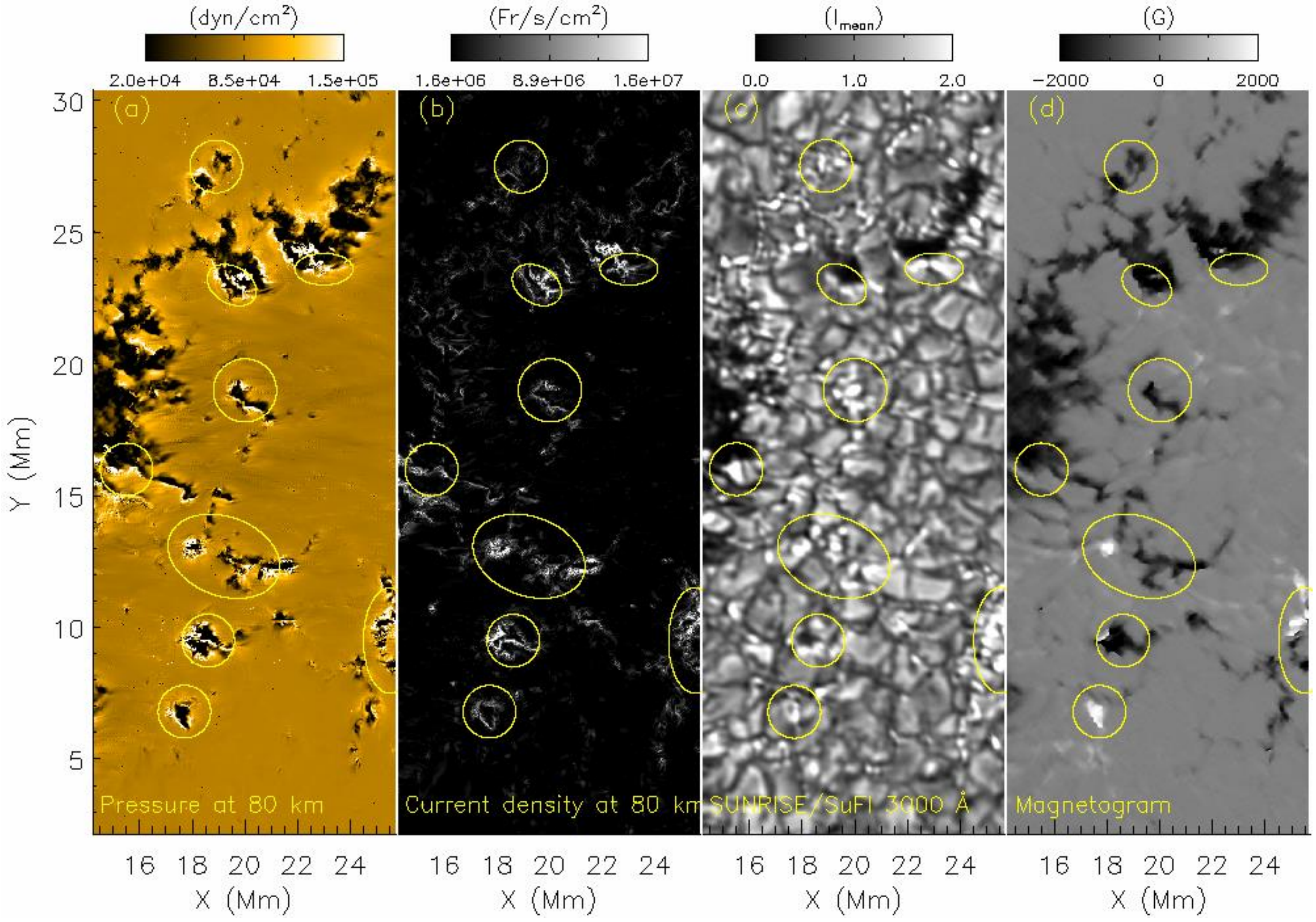


IMaX+HMI magnetogram
Extrapolation: 2336*1824*128



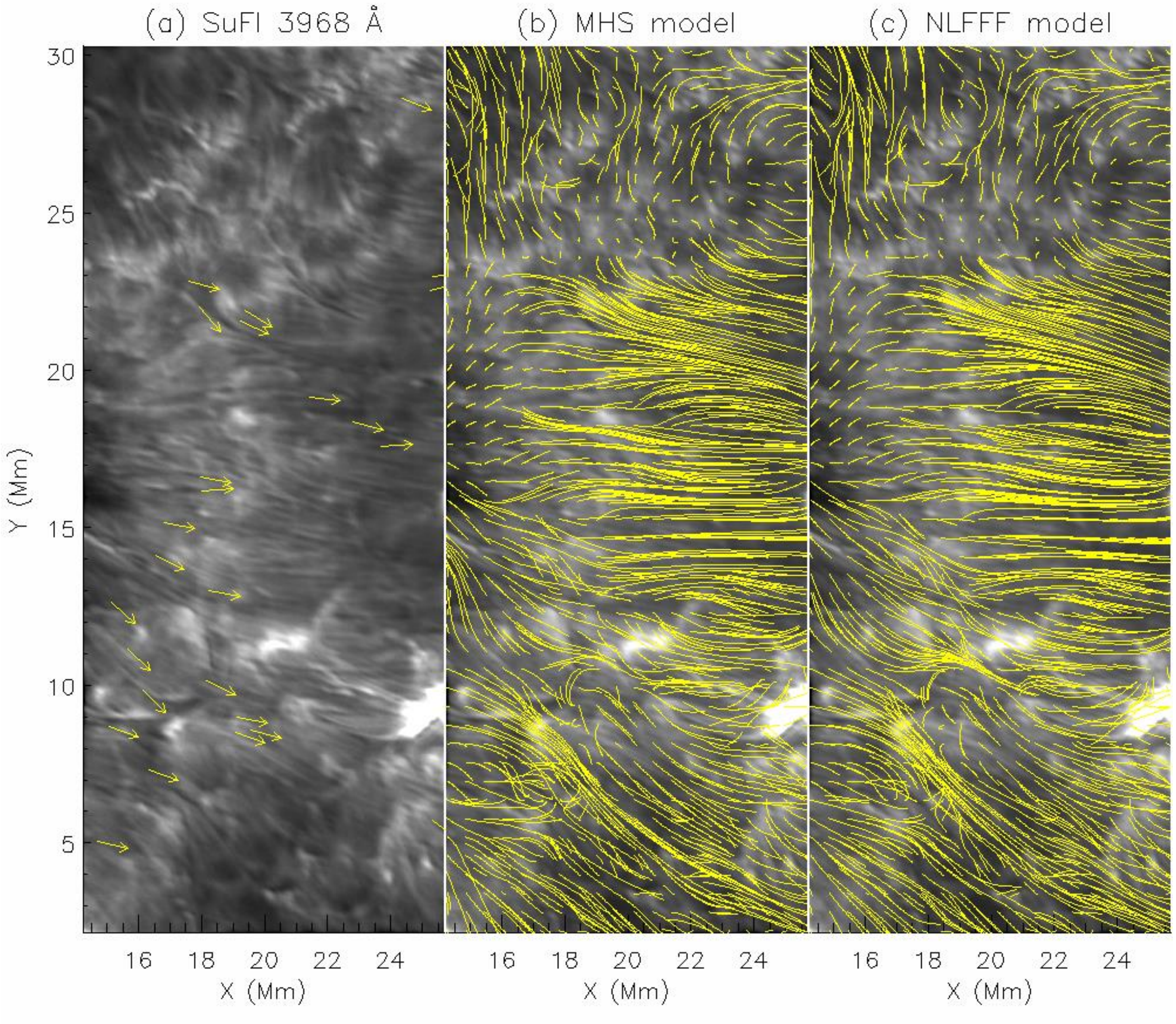
Max-Planck-Institut für Sonnensystemforschung

- Weak plasma in the active region because of the strong magnetic field
- Fibril-like plasma pattern traces magnetic field lines due to the low plasma β (seen from different perspectives)



- Bright points are clearly seen in the inter-granular lanes in panel (c), which are typically regarded as nearly vertical slender flux tubes with kG magnetic fields

- Regions of high gas pressure and strong electric current coincide, most of which are located near the edges of magnetic flux tubes



Max-Planck-Institut für Sonnensystemforschung

- Field lines trace chromospheirc fibrils well
- Angel between magnetic vector and fibril orientation: θ
- For selected 26 fibrils:

$$\bar{\theta}_{mhs} \approx 11.8°$$

$$\bar{\theta}_{nlff} \approx 15.7°$$

Outline

- The magnetohydrostatic (MHS) extrapolation
- Test with a Low’s special MHS solution
- Test with a radiative MHD simulation
- Apply to a SUNRISE/IMaX vector magnetogram
- **Summary**

Summary

1. An optimization-type MHS extrapolation is developed, tested and applied to real data.
2. Tests show that the MHS extrapolation is able to (1) recover main structures of plasma below 1Mm, (2) generate a more precise magnetic field than that by the NLFFF extrapolation.
3. Application shows (1) weak plasma in strong field region, (2) fibril-like plasma pattern trances the magnetic field, (3) photospheric high pressure and strong current regions around the magnetic flux tube, (4) magnetic vectors obtained by the MHS extrapolation are more aligned with chromospheric fibrils.

Reference

[1] Gary, G. A. 2001, Sol. Phys., 203, 71

[2] Wheatland, M. S., Sturrock, P. A., & Roumeliotis, G. 2000, ApJ, 540, 1150

[3] Wiegelmann, T. 2004, SoPh, 219, 87

[4] Zhu, X., & Wiegelmann, T. 2018, ApJ, 866, 130

[5] Zhu, X. & Wiegelmann, T. 2019, A&A, 631, A162

[6] Zhu, X., Wiegelmann, T., & Solanki, S. 2020, A&A, submitted

[7] Low, B. C. 1991, ApJ, 370, 427

[8] Cheung, M. C. M., Rempel, M., Chintzoglou, G., et al. 2019, Nat. Astron., 3, 160

[9] Vögler, A., Shelyag, S., Schüssler, M., et al. 2005, A&A, 429, 335

[10] Rempel, M. 2017, ApJ, 834, 10

[11] Solanki, S. K., Riethmüller, T. L., Barthol, P., et al. 2017, ApJs, 229, 2

Max-Planck-Institut für
Sonnensystemforschung

Thank you for your attention!