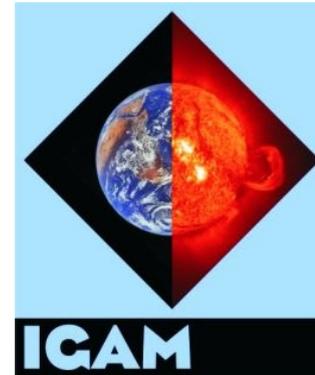




universität
wien



Tracking of photospheric shock waves in computational fluid dynamics data

P. Leitner¹, B. Lemmerer¹, A. Hanslmeier¹, T. Zaqarashvili^{1,2,3}
J. Koza⁷, M. Temmer¹, A. Veronig¹, H. Grimm-Strele^{4,5},
H.J. Muthsam⁴, F. Calvo⁶, O. Steiner⁶

¹ Institute of Physics - IGAM, University of Graz

² Space Research Institute, Austrian Academy of Sciences

³ Abastumani Astrophysical Observatory at Ilia State University

⁴ Faculty of Mathematics, University of Vienna

⁵ Max-Planck Institute for Astrophysics, Garching

⁶ Kienerheuer-Institut für Sonnenphysik, Freiburg

Outline

- Present the **ANTARES** code/specific model photosphere
- Studies of our workgroup based on the obtained model data
- Describe shock wave detection algorithms
- Show first results obtained by post-processing application to our simulation data

The ANTARES RHD code

- Over more than a decade fully matured RHD code [Muthsam et al. 2007, 2010]
- Heavily under development with an imminent RMHD upgrade to be released
- Applications: photospheric turbulence [Muthsam et al. 2007], Cepheid pulsations [Muthsam et al. 2011], ...

Recent developments:

- Consideration of two-component flows [Zaussinger 2010]
- A parallel multigrid solver [Happenhofer et al. 2013]
- Solver for Navier–Stokes–Eqns on curvilinear grids [Grimm–Strele et al. 2014]

Basic equations of radiation hydrodynamics

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Euler's equation of momentum balance

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{M} - \sigma) = \mathbf{f}$$

Energy balance equation

$$\frac{\partial e}{\partial t} + \nabla \cdot (\mathbf{u}(e + P) - \mathbf{u} \cdot \boldsymbol{\tau}) = \rho(\mathbf{g} \cdot \mathbf{u}) + Q_{\text{rad}}$$

Radiation transfer equation

$$\hat{\mathbf{r}} \cdot \nabla I_{\nu} = \rho \kappa_{\nu} (S_{\nu} - I_{\nu})$$

The ANTARES code – Numerical schemes

- **ANTARES distinguished by its elaborate numerical schemes and numerical stability**
- **Finite volume methods are prone to numerical oscillations at discontinuities**
 - Traditional remedies:
 - Introduction of artificial viscosity
 - Application of limiters
 - In ANTARES weighted essentially non-oscillatory finite volume (WENO) schemes are implemented [Kupka et al. 2012]
- **Treatment of turbulence by adopting local mesh refinement**
- **Boundary conditions**
 - periodic for all quantities in horizontal directions
 - open at the bottom and top: allowing for convective mass- and energy in- and outflow
 - transmissive for waves

ANTARES RHD model photosphere

- **Grid size**

$$N_x \times N_y \times N_z = 405 \times 511 \times 511$$

- **Vertical range:**

~ 4 Mm below and

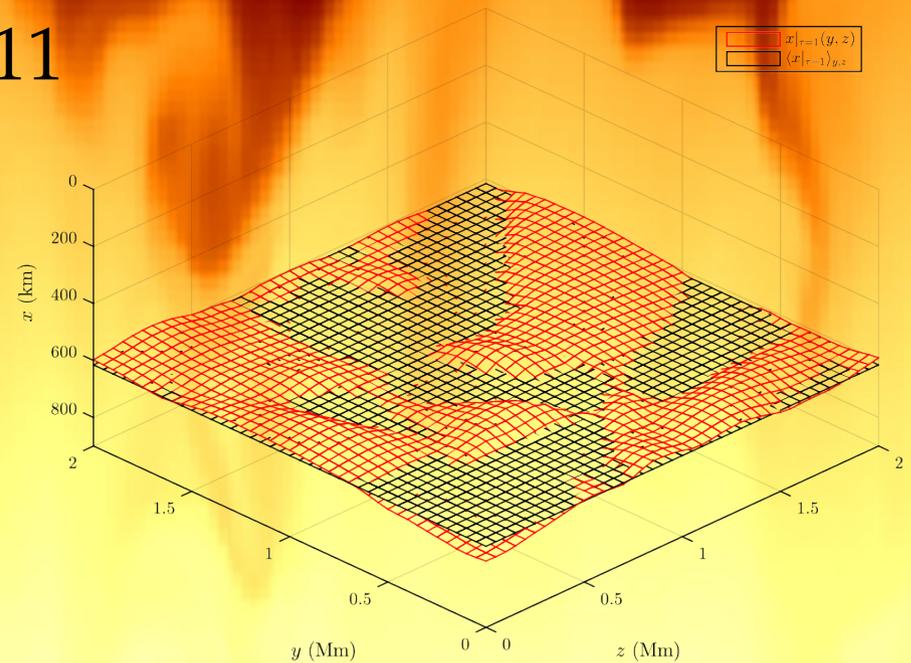
0.6 Mm above the solar surface

- **Horizontal range:**

18 Mm x 18 Mm

- **Spatial resolution:**

$$\Delta x = 11.0 \text{ km}, \Delta y = \Delta z = 35.3 \text{ km}$$



Optical depth unity isosurface and its horizontal average displayed on a 2 Mm x 2 Mm subgrid

Study of the photospheric structure

- Studied vertical photospheric stratification and layers of distinguished dynamical characteristics by correlation analysis

Astrophys Space Sci (2017) 362:181
DOI 10.1007/s10509-017-3151-7



ORIGINAL ARTICLE

Structure of the solar photosphere studied from the radiation hydrodynamics code **ANTARES**

P. Leitner¹  · B. Lemmerer¹ · A. Hanslmeier¹ · T. Zaqarashvili^{1,2,3} · A. Veronig¹ · H. Grimm-Strele^{4,5} · H.J. Muthsam⁴

Study of dynamical processes in the photosphere

Two-dimensional segmentation of small convective patterns in radiation hydrodynamics simulations

10⁵
n/s

Astronomy & Astrophysics manuscript no. aa28011_Lemmerer
November 22, 2016

©ESO 2016

Dynamics of small-scale convective motions

B. Lemmerer¹, A. Hanslmeier¹, H. Muthsam², and I. Piantschitsch¹

¹ Institute of Physics, IGAM, University of Graz, Universitätsplatz 5, 8010 Graz, Austria

² Institute of Mathematics, University of Vienna, Oskar-Morgenstern-Platz 1, 1090 Wien, Austria

ROTATING PLASMA JETS IN THE PHOTOSPHERIC INTERGRANULAR LANES

B. LEMMERER¹, T. V. ZAQRASHVILI^{1,2,3}, P. LEITNER¹, A. HANSLMEIER¹, I. PIANTSCHITSCH¹, AND H. MUTHSAM⁴

¹IGAM, University of Graz, Universitätsplatz 5, 8010 Graz, Austria

²Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, 8042 Graz, Austria

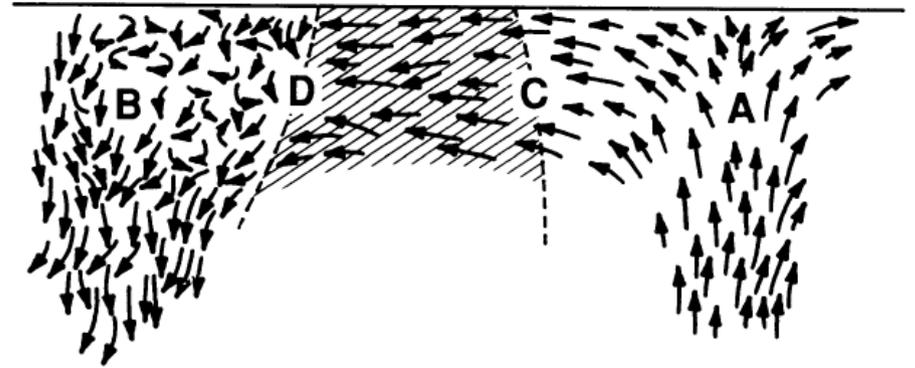
³Abastumani Astrophysical Observatory at Ilia State University, Kakutsa Cholokashvili Ave 3/5, 0162 Tbilisi, Georgia and

⁴Institute of Mathematics, University of Vienna, Oskar-Morgenstern-Platz 1, 1090 Wien, Austria

Draft version March 13, 2017

Shock formation in the solar granulation

- **Overturning matter cools non-adiabatically turning transonic in highly localized regions**
- **Transition of transonic horizontal flows to turbulent subsonic downflows drives shock waves**
- **Shocks propagate upstream, weaken and finally dissolve**
- **Fluctuations are amplified by propagating shock waves**



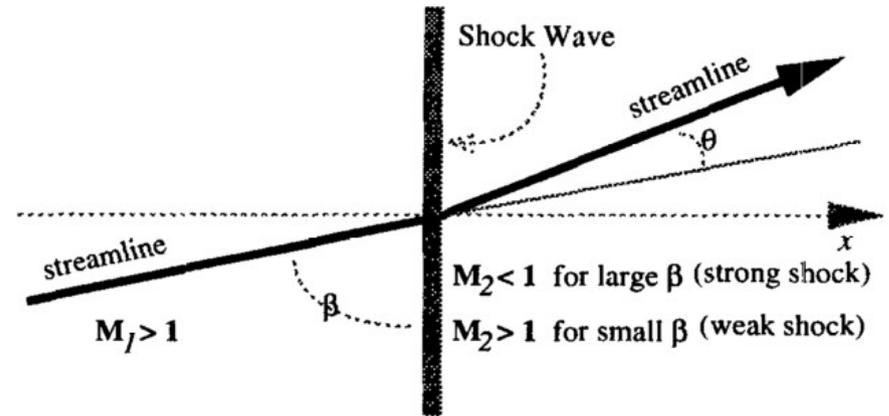
Supersonic horizontal flows at granular borders decelerate to subsonic velocities at (D). The abrupt transition corresponds to a shock wave.

From: A. Nesis, T.J. Bogdan, F. Cattaneo et al. 1992

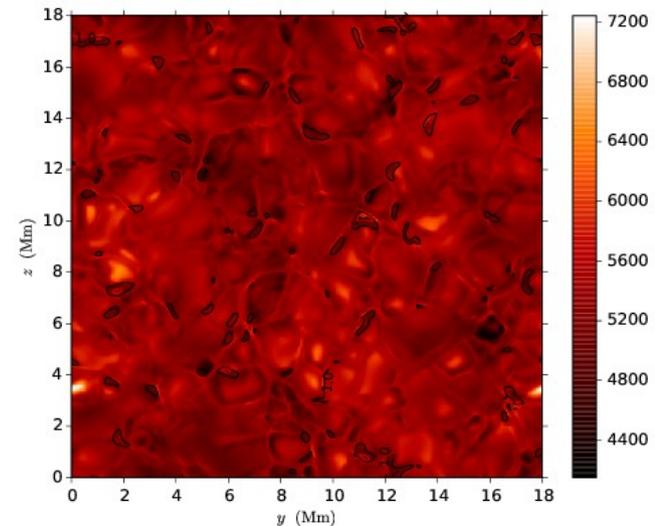
Motivation for shock front segmentation

- Mach number contours/isosurfaces also include oblique shocks
- Normal shock waves are subset of broader class of oblique shock waves
- □ Identification of surfaces where $M_{\perp} = 1$
- Workaround: Approximation of the direction normal by $\nabla \rho$ [Ma et al. 1996], i.e.

$$M_{\perp} \approx \frac{u}{c_s} \cdot \frac{\nabla \rho}{\|\nabla \rho\|}$$



A 1-D oblique shock [Ma et al. 1996]



Post-processing techniques for shock detection:

1) Directional derivative thresholding

[Pagendarm, H.G. and Seitz, B. 1993]

- **Location of a discontinuity can be approximated by the position of steepest gradient**

$$\delta_1 \varrho = \frac{\partial \varrho}{\partial n} = \frac{\mathbf{u}}{\|\mathbf{u}\|} \cdot \nabla \varrho \stackrel{!}{=} \max$$

$$\delta_2 \varrho = \frac{\partial^2 \varrho}{\partial n^2} = \frac{\mathbf{u}}{\|\mathbf{u}\|} \cdot \nabla \left(\frac{\mathbf{u}}{\|\mathbf{u}\|} \cdot \nabla \varrho \right) = 0$$

Shock detection procedure:

1) Evaluate first and second directional derivatives for all grid points

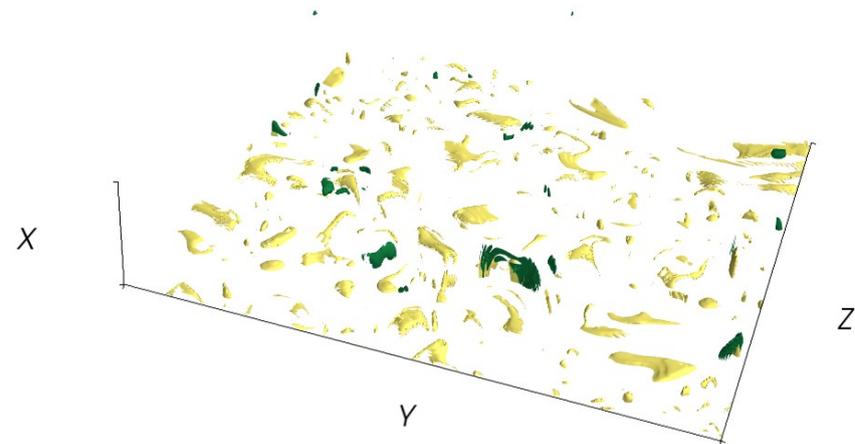
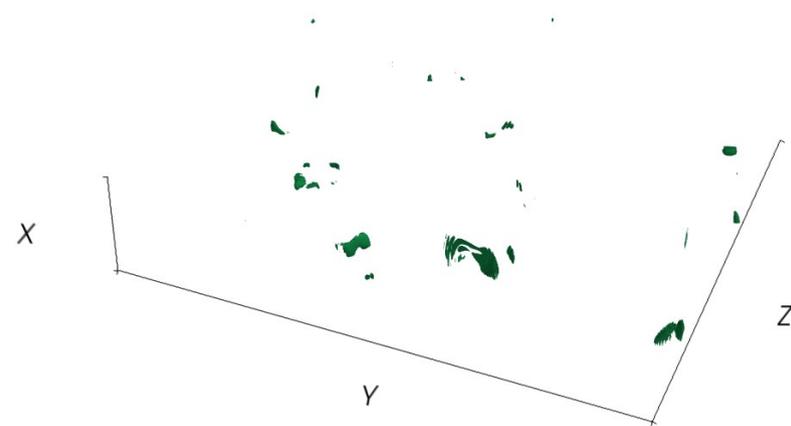
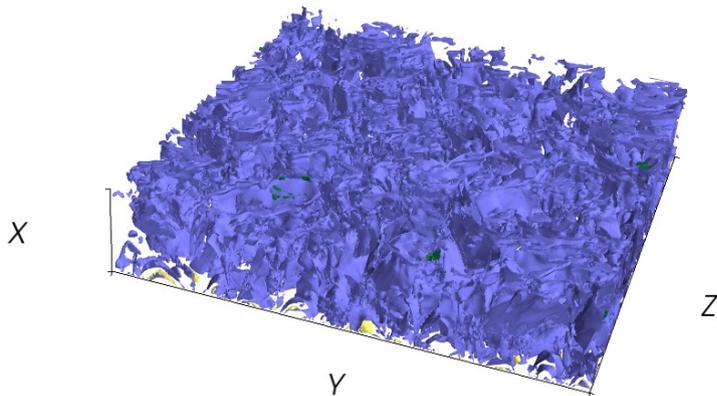
2) Construct zero-level iso-surfaces of the 2nd directional derivative

3) Discard points on these iso-surfaces, where $\delta_1 \varrho < \epsilon$

4) Further discard points where $M_{\perp} \neq 1$

Application of procedure 1 to the ANTARES model atmosphere

- Maxima of the directional density gradient (step 2, purple surfaces) fill large areas of the box
- Choose threshold value (step 3) as lower limit for first derivative (yellow surfaces)
- 1-Isosurfaces of perp. Machnumber (step 4, green surfaces)
- Apply both filter on $\delta_2 \rho = 0$ ISOSURFACES



Shock wave detection procedure #2

Method based on normal Mach number by [Lovely and Hames 1999]

Method has 2 variants for detecting
a) stationary and b) transient shocks

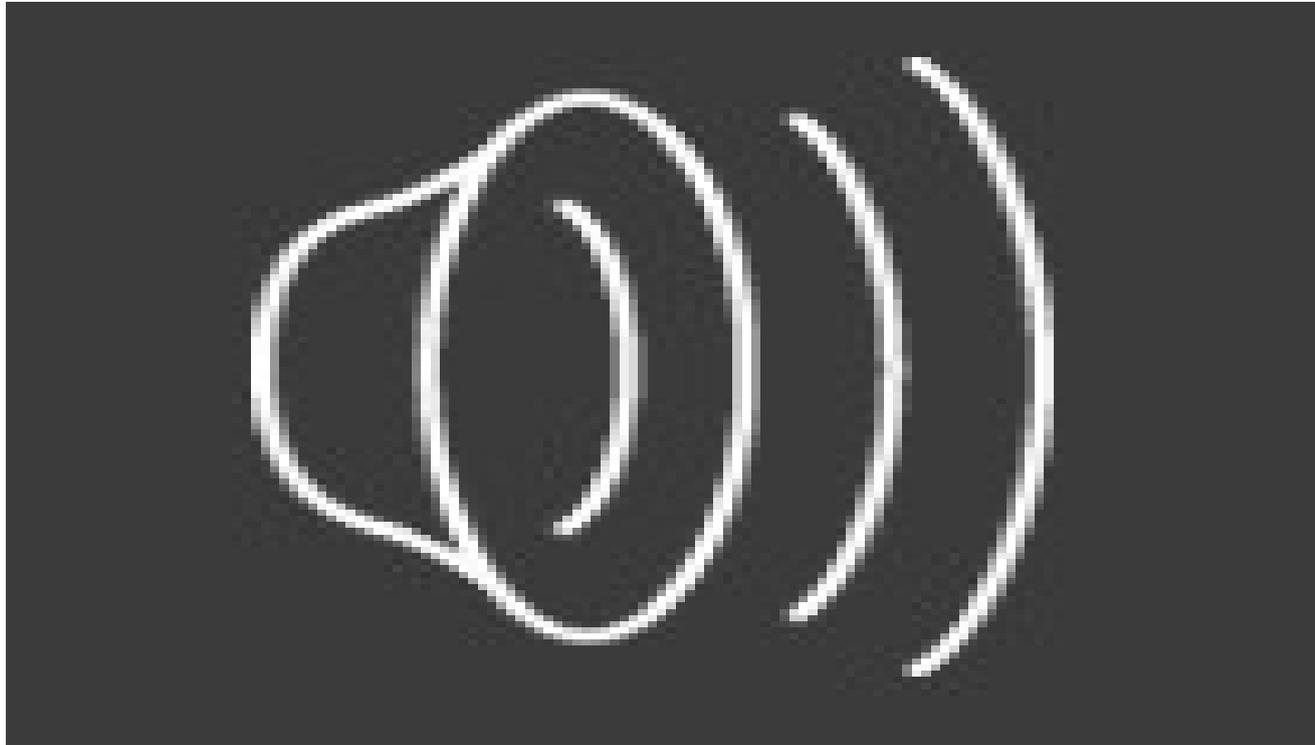
- Variant a) is exactly filter number 4 of the preceding method
- Variant b) transient shocks; condition $M_{\perp} = 1$ becomes

$$\frac{1}{\|\nabla P\|} \cdot \frac{1}{c_s} \cdot \frac{DP}{Dt} = \frac{1}{\|\nabla P\|} \cdot \frac{1}{c_s} \cdot \frac{dP}{dt} + \frac{M \cdot \nabla P}{\|\nabla P\|} \stackrel{!}{=} 1$$

- Filters:

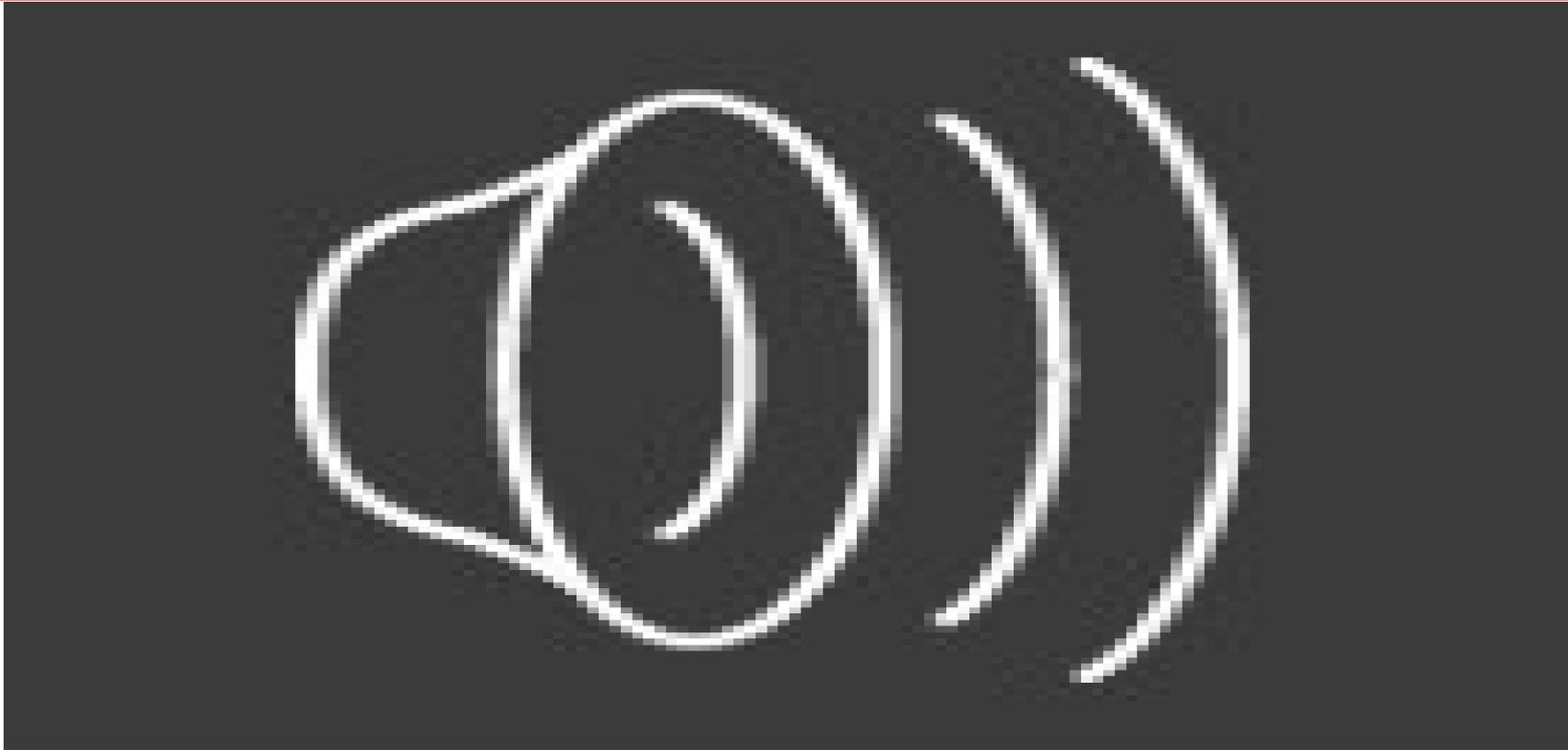
$$\frac{|\nabla P \cdot \mathbf{n}|}{\|\nabla P\|} \leq c, \quad \frac{\|\nabla P\|}{\|\nabla P\|_{\max}} \geq \eta$$

Results: Shock front segmentation for the ANTARES RHD model atmosphere



- Application of Lovely–Haimes algorithm for transient shock waves
- It needs to be further looked into how much the shock sizes are affected by fine-tuning parameters c and α

Comparison with shocks detected in RMHD data



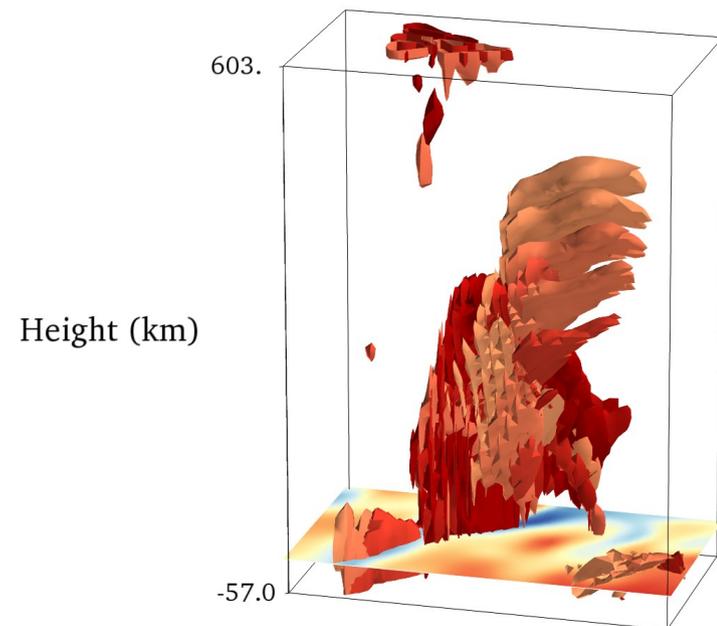
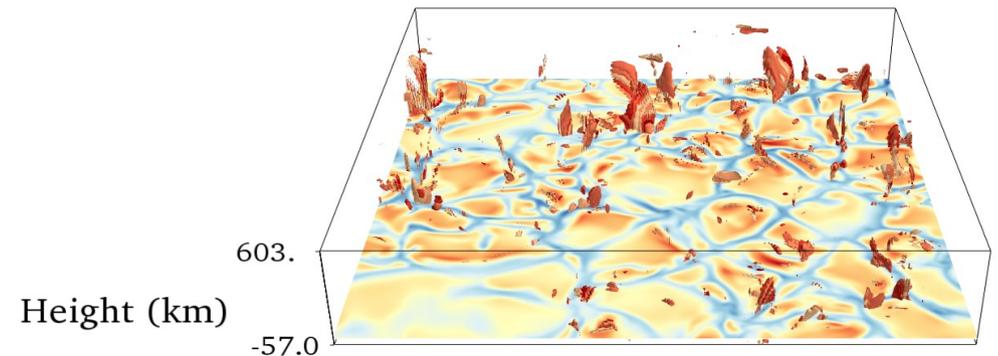
- Application of Lovely-Haimes algorithm on CO5BOLD data
- Modified hydromagnetic energy jump-condition:

$$\frac{1}{2}u_1^2 + \frac{\gamma}{\gamma - 1} \frac{P_1}{\rho_1} + \frac{B_1^2}{4\pi\rho_1} = \frac{1}{2}u_2^2 + \frac{\gamma}{\gamma - 1} \frac{P_2}{\rho_2} + \frac{B_2^2}{4\pi\rho_2}$$

Tracking of the temporal evolution of HD shock fronts

Study of shock propagation driven by aims:

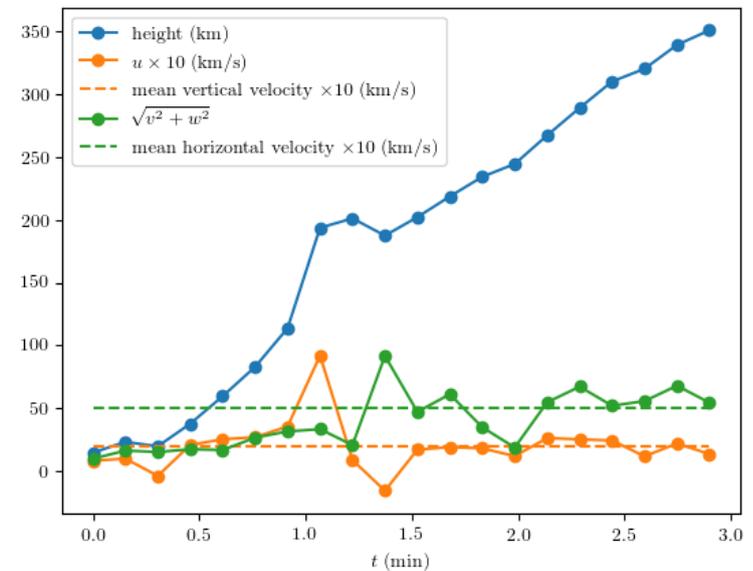
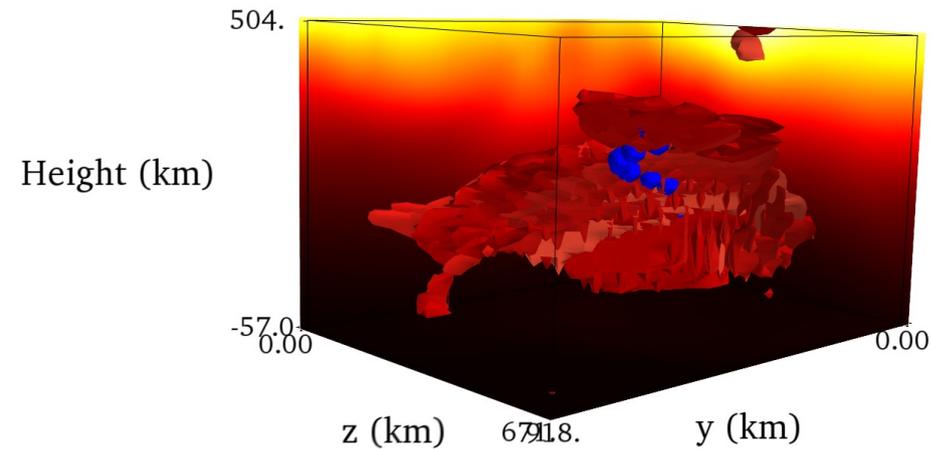
- Identification of the emission regions and wave drivers
- Study of the morphology and kinematics of photospheric shocks
- Quantification of the energy transport through shocked acoustic waves
- Location of height levels of wave dissipation within the photosphere



Case study:

i) Ascending shock

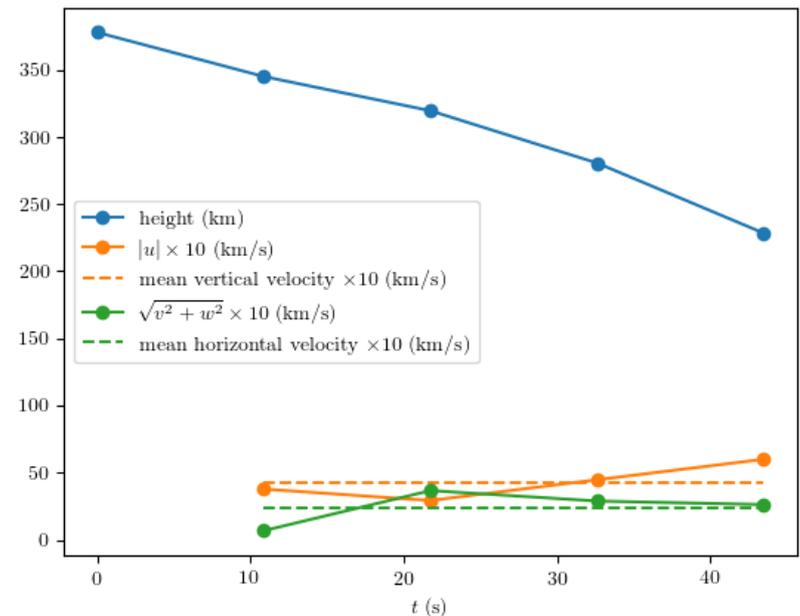
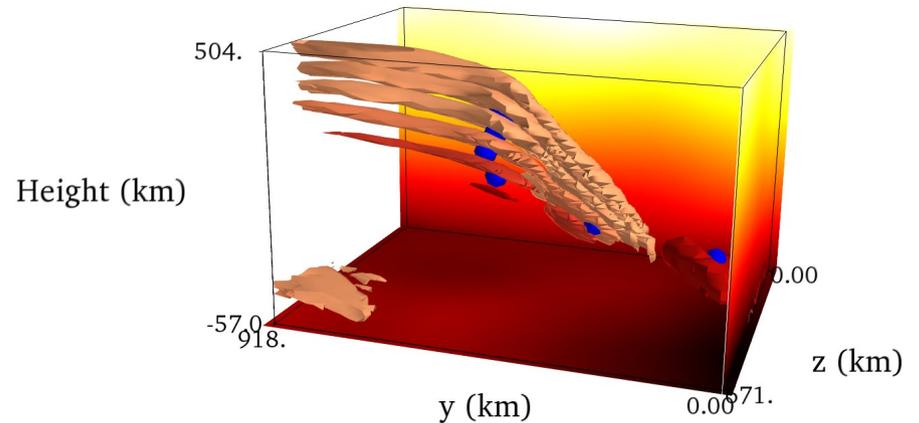
- Using c.m. R_{cm} of segmented fronts for first rough description of the wave kinematics
- Emerges from below the photosphere
- Rises almost steadily to a height of \square 350 km before dissolution
- Propagation faster \square 5.5 km/s in ascending phase
- Horizontal velocity on average more than twice as large as vertical component



Case studies:

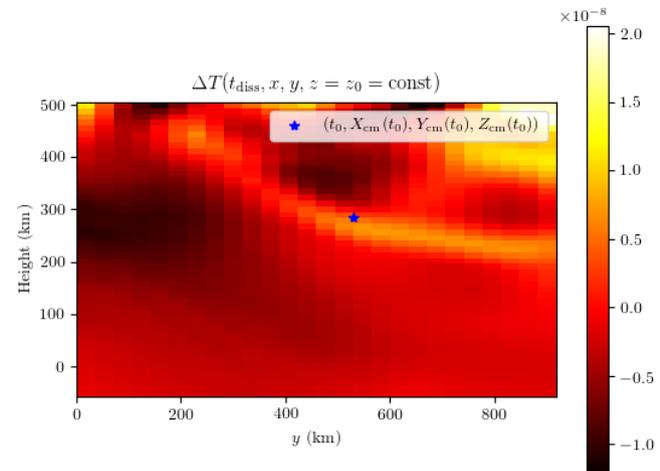
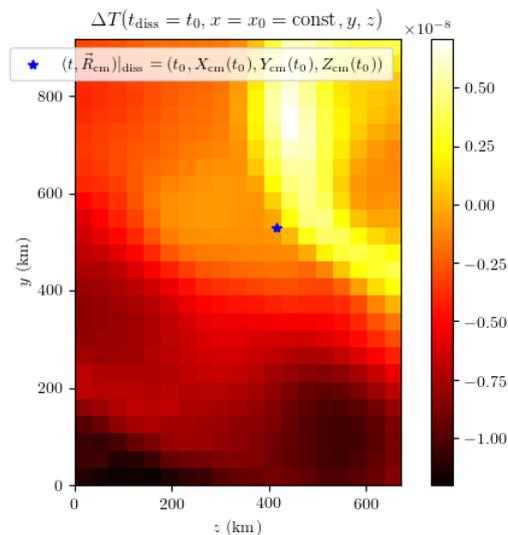
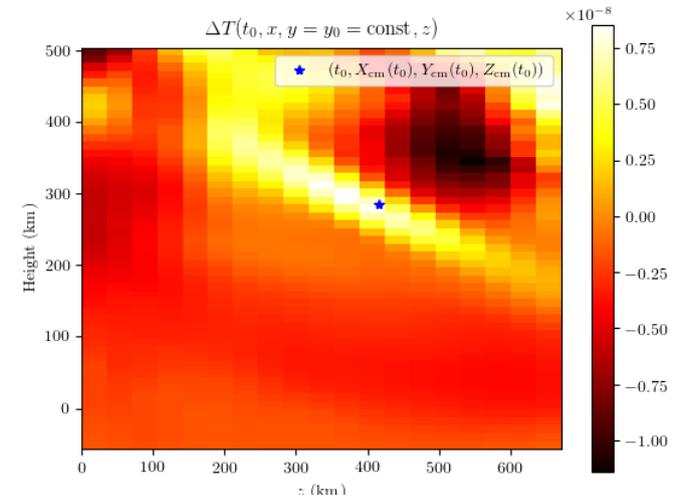
ii) Wave dissipation within the photosphere

- Reaching point of highest ascent in the high photosphere then propagating downwards at \square 4 km/s, dissolving in the middle photosphere
- Descending waves at end of their lifetime slower than upwards moving waves emerging from the convection zone
- Vertical velocity component almost twice as large as the horizontal component



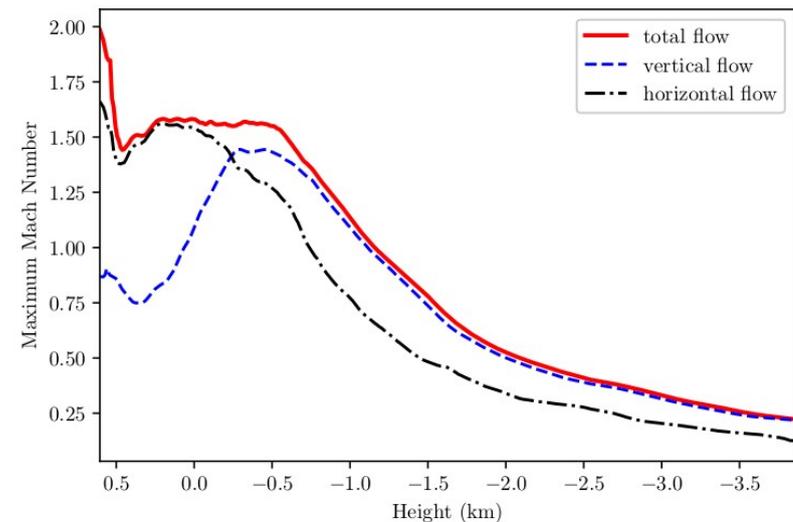
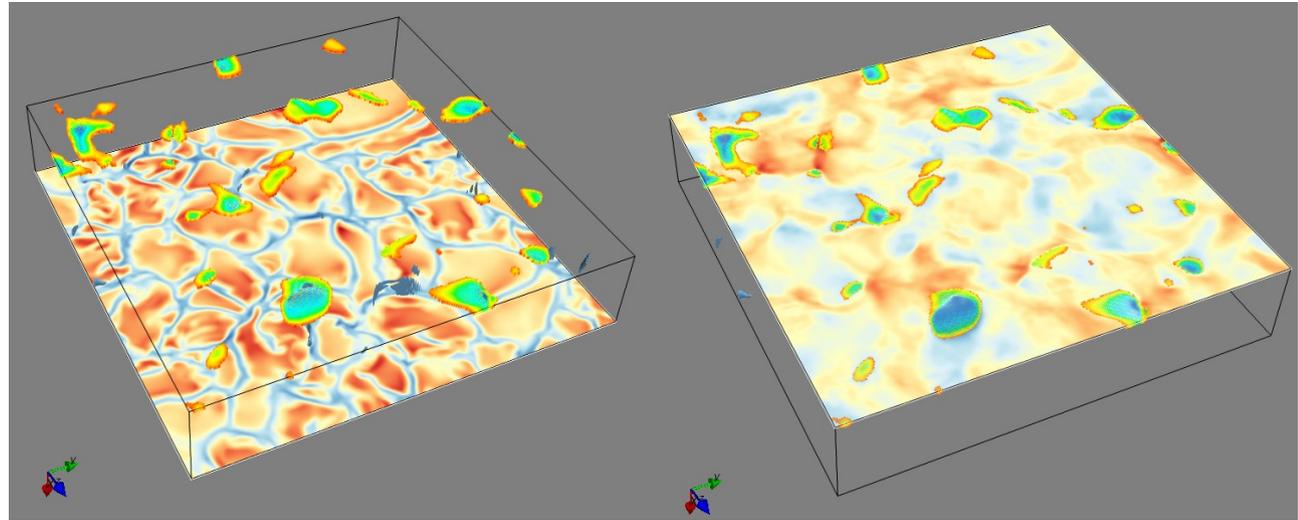
Case ii) Dissolution and dissipation of the descending shock wave

- In all coordinate planes intersecting with $R_{cm}(t_{fin})$ a small temperature increase in the vicinity is found



Correlation of shock fronts with the underlying flow pattern

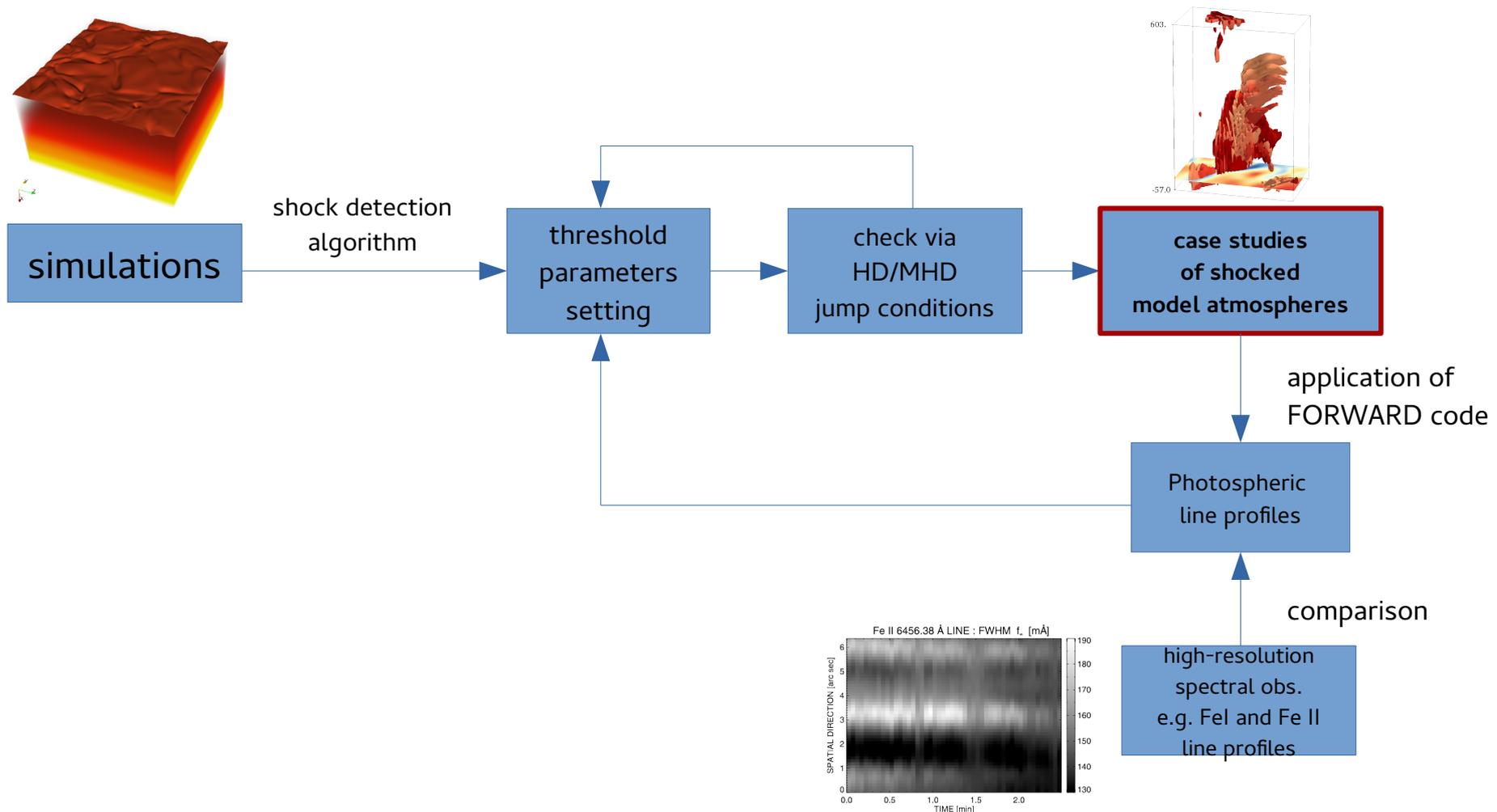
- Propagation of shocks channelled in the intergranular lanes
- Correlation still very strong in the high photosphere
- Horizontal velocity increases with height, while vertical velocity is almost constant during ascending/descending phases
- Maximum Machnumbers in the higher photosphere mostly in vertical flow component



Outlook on further activities

- **Further case studies of wave propagation/statistical evaluation of shock wave kinematics**
- **ANTARES RMHD model photosphere**
 - Study Poynting flux and full hydromagnetic energy transport across the photosphere
 - Possibility to study wave propagation into the chromosphere and quantify the heating of this layer due to acoustic and MHD waves
- **Comparison to observations**
 - Fine-tuning of threshold parameters from estimation of shock sizes

Outlook: 2-step verification of segmentation results



From: Rybak et al. 2004

Summary

- In parts, shocks emerge from below the photosphere inside the intergranular lanes
- High correlation between shock regions and intergranular flow field throughout the photosphere
- Some shocks turn over in the higher photosphere and descend again before dissolving and heating the surrounding matter
- Supersonic flows (possible drivers for shocks) found into a depth of 1.5 Mm below the surface
- In the higher photosphere it is mostly horizontal flows that are supersonic, below the surface also the vertical are found to turn transonic