IDENTIFICATION OF VORTEX MOTION IN SOLAR ATMOSPHERE

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VORTEX MOTION (MOTIVATION)

- Vortical motions appeared in simulations of magneto-convection e.g. Nordlund, 1985; Cattaneo et al. 1991; Hurlburt, Toomre, and Massaguer, 1986; Stein and Nordlund, 1991.
- Potential to excite MHD waves, slow fast and Alfven (Fedun et al. 2011).
- Can form twisted magnetic flux tubes (Shelyag et al. 2011; Kitiashvili et al. 2012)
- Photospheric vortices and coronal heating (Zirker, Solar Physics, 1993), Believed to be able to account for the heating of the higher solar atmosphere layers
- Excitation of Acoustic Waves by Vortices in the Quiet Sun (Kitiashvili et al. 2011, ApJL)
- S.Wedemeyer-Böhm and L. Rouppe van der Voort, A&A, 2009
- Sven Wedemeyer-Bohm, Eamon Scullion, Oskar Steiner, Luc Rouppe van der Voort, Jaime de la Cruz Rodriguez, Viktor Fedun & Robert Erdelyi, Magnetic tornadoes as energy channels into the solar corona, Nature, 2012
- Small-scale dynamo magnetism as the driver for heating the solar atmosphere, (Tahar Amari, et al. Nature, 2015)

Their identification and categorization relied primarily on

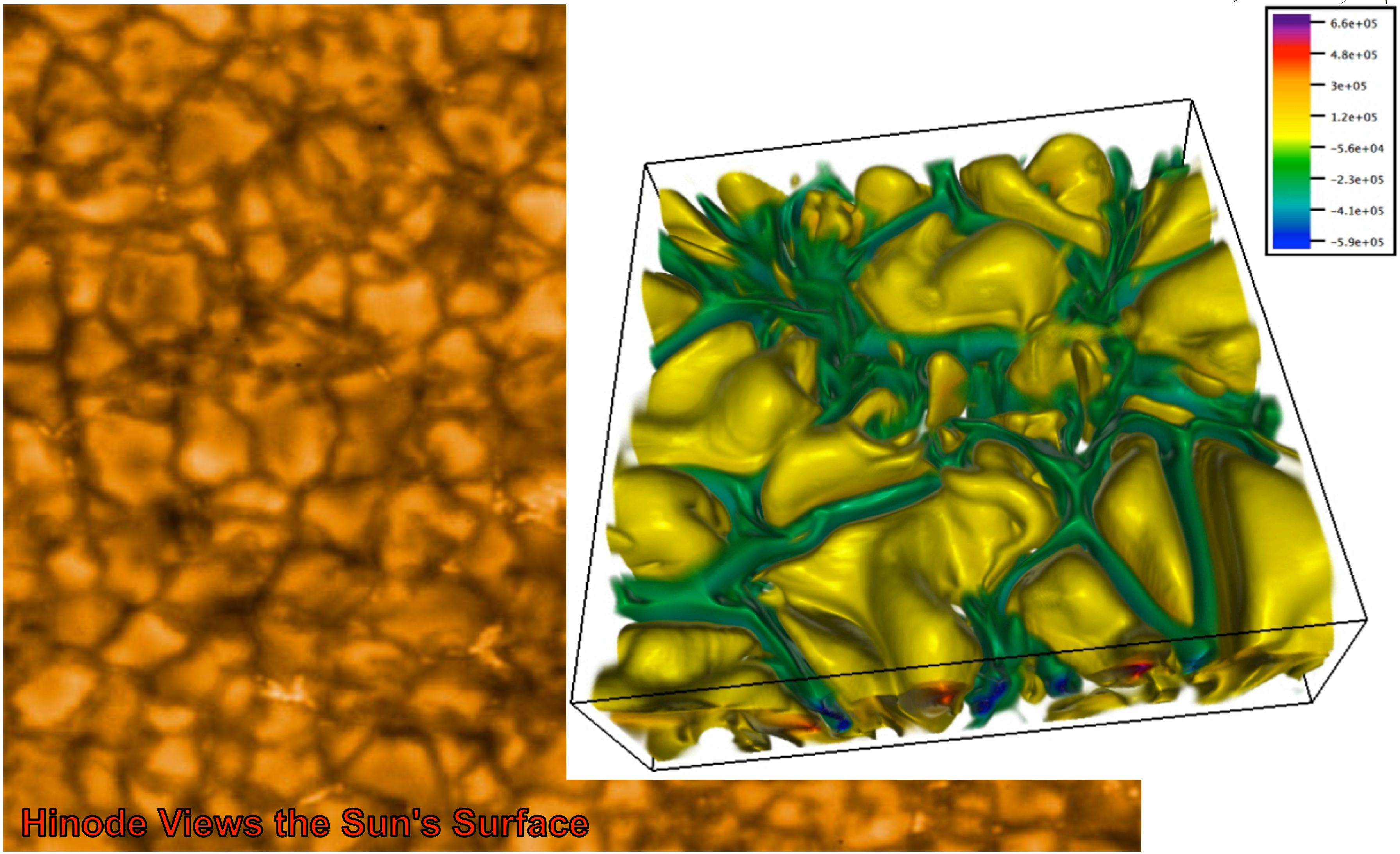
1) visual inspection using intensity,

e.g. for example Bonet et al. 2008 (“**The identification of each particular BP has been carried out by eye, playing back and forth the movie with the FOV of the event**”)

Vargas Domínguez et al. 2011 ; Park et al. 2016

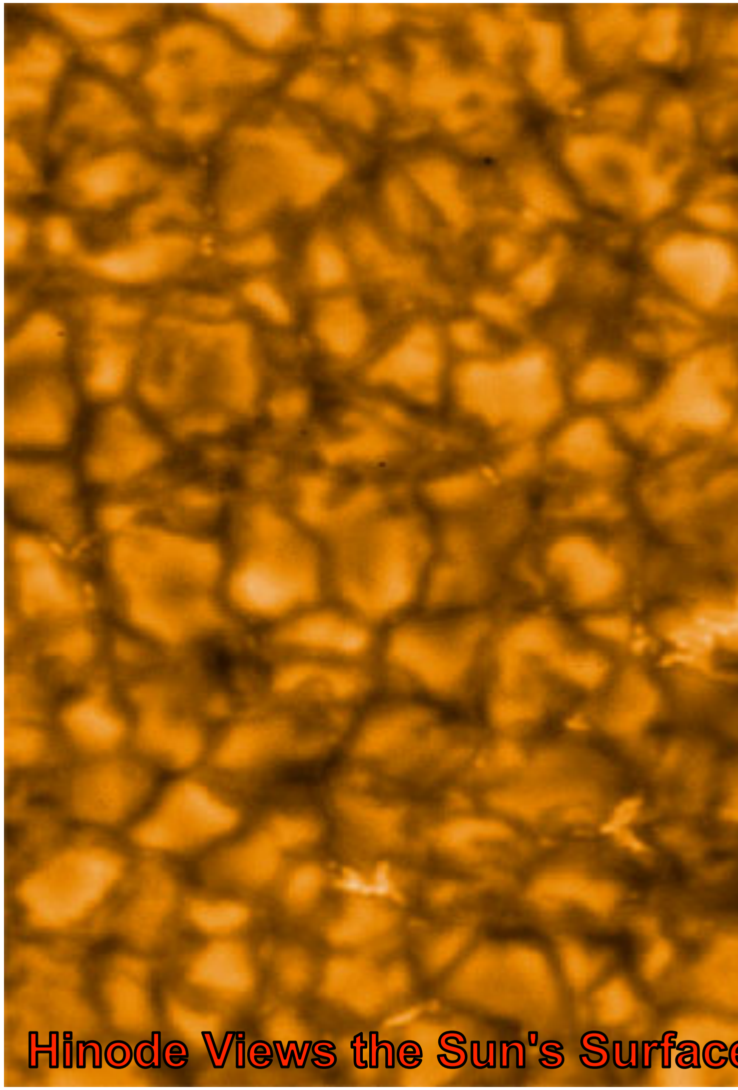
2) or a mixture of velocity field identification and visual inspection (e.g. Bonet et al. 2010).

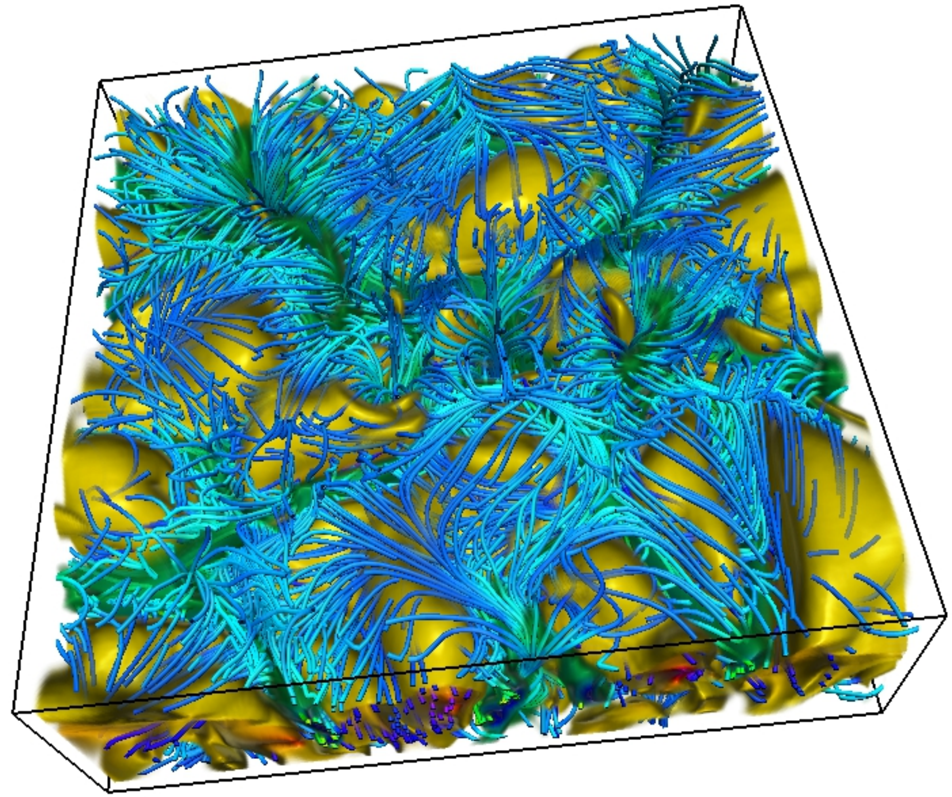
NUMERICS 3D MHD: MAGNETO-CONVECTION SIMULATION



Fedun et al, *AnGeo*, 2011, Shelyag, Fedun, Keenan, Erdélyi, Mathioudakis, *AnnGeo*, 2011

NUMERICS 3D MHD: MAGNETO-CONVECTION SIMULATION





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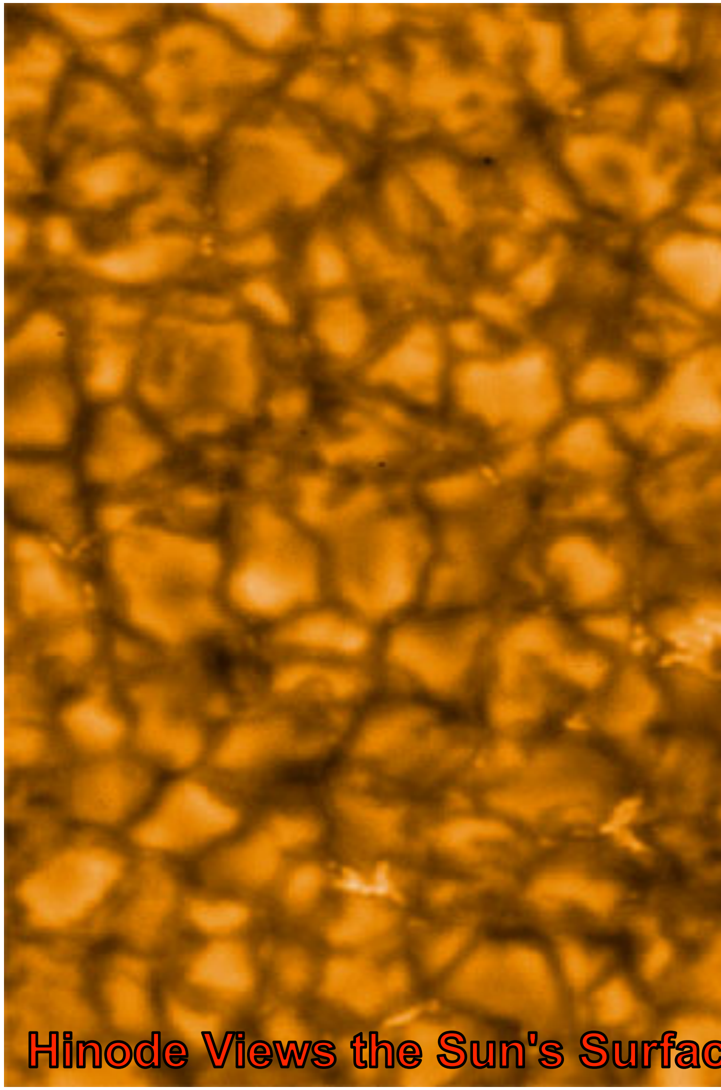

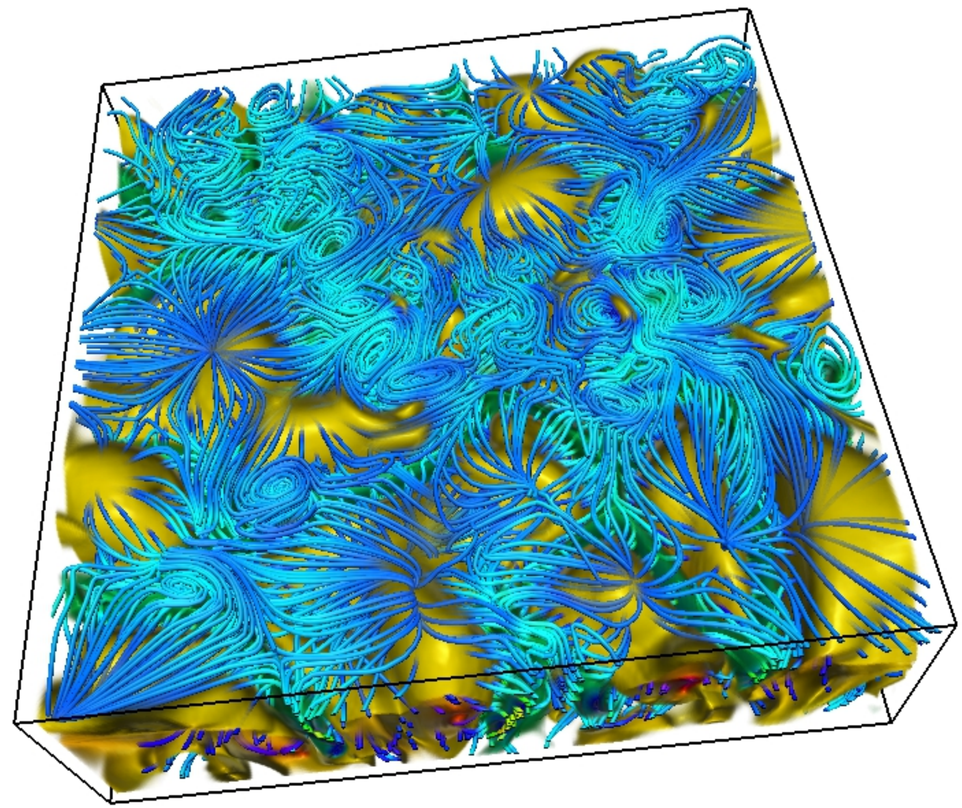

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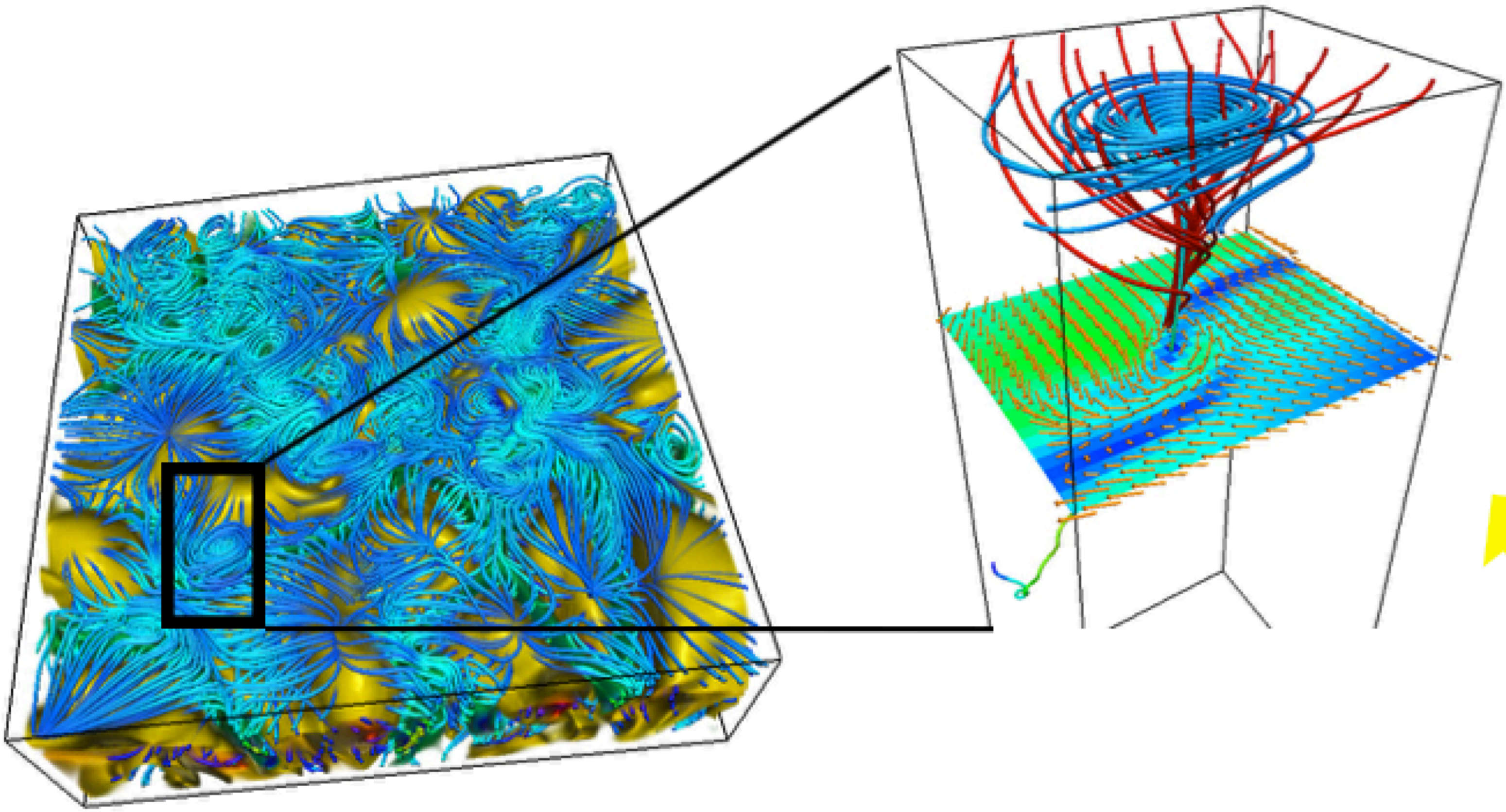

3D MAGNETIC FLUX TUBE

The University Of Sheffield.

Solar Physics and Space Plasma Research Centre (SP^{2}RC)

Viktor Fedun and Robert Erdelyi
v.fedun, robertus@sheffield.ac.uk
http://swat.group.shef.ac.uk/simulations.html

MHD Waves in 3D Flux Tube

- Driver period: P=120 s
- Driver amplitude: A=200 m/s
- Driver distance: R=100 km
- Footpoint flux tube radius: R=100 km
- Footpoint magnetic field: B=1000 G
- Domain ([Dx, Dy, Dz] = [2 Mm, 2 Mm, 1.6 Mm])
- Gridpoints [Nx, Ny, Nz] = [100, 100, 196]
- **b_x component of magnetic field**

12 Jan 2010

SWAT Solar WAve Theory Group

VAPOR Visualization & Analysis Platform

The University Of Sheffield.

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MHD Waves in 3D Flux Tube

- Driver period: P=120 s
- Driver amplitude: A=200 m/s
- Driver distance: R=100 km
- Footpoint flux tube radius: R=100 km
- Footpoint magnetic field: B=1000 G
- Zoom in of the full domain ([Dx, Dy, Dz] = [2 Mm, 2 Mm, 1.8 Mm]) focusing on the region Dx, Dy = 0.8 – 1.2 Mm, Dz=0 – 0.9Mm
- Gridpoints [Nx, Ny, Nz] = [100, 100, 196]

12 Jan 2010

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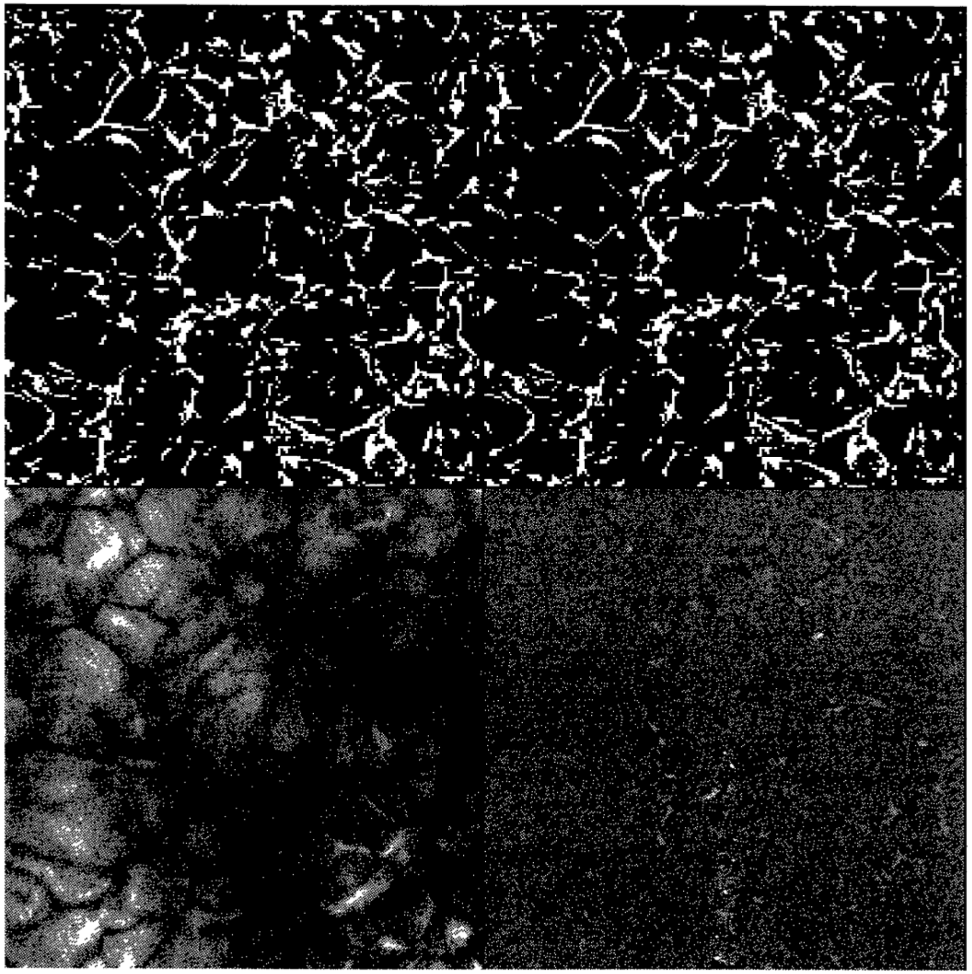
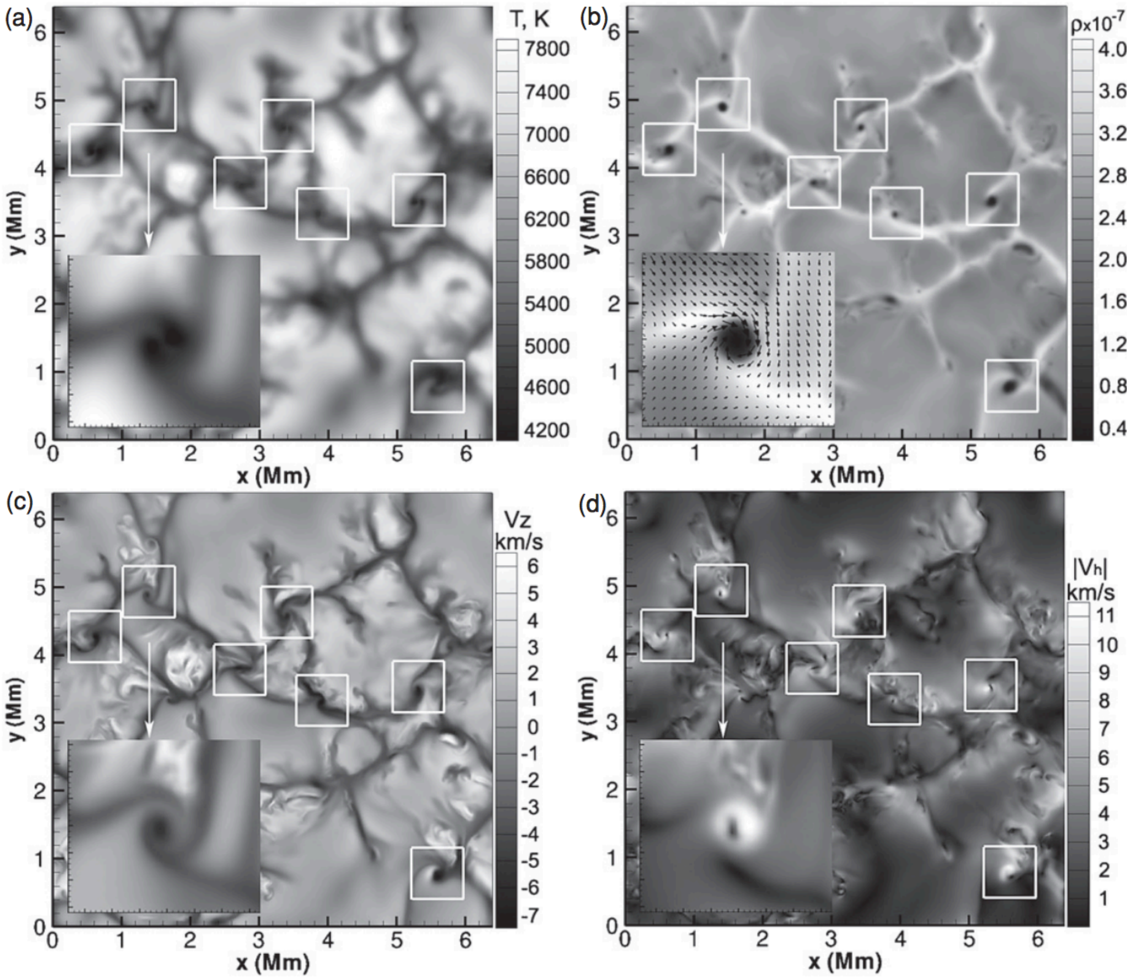
VORTEX MOTION (MOTIVATION)



Photospheric vortices and coronal heating

J. Zirker, Sol. Phys. 1993

VORTEX MOTION (MOTIVATION)



Snapshots of the simulation results at the solar surface for (a) temperature, (b) density, (c) vertical velocity, and (d) magnitude of the horizontal velocities.

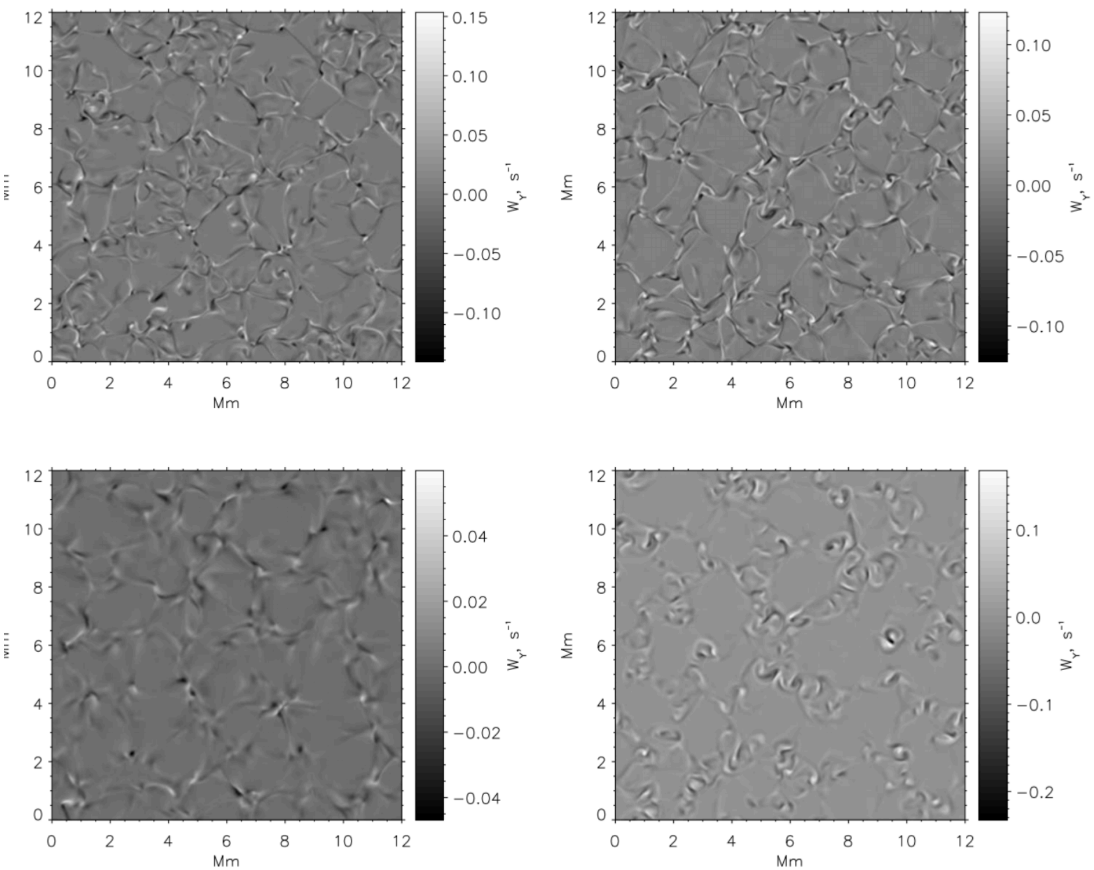
White squares indicate the largest whirlpools. The whirlpools are located in the intergranular lanes. One of these whirlpool is magnified and shown in the left corner of

each panel. The insertion in panel (b) also shows the horizontal velocity field by arrows. The longest arrows correspond to approximately 10 km s−1. The horizontal

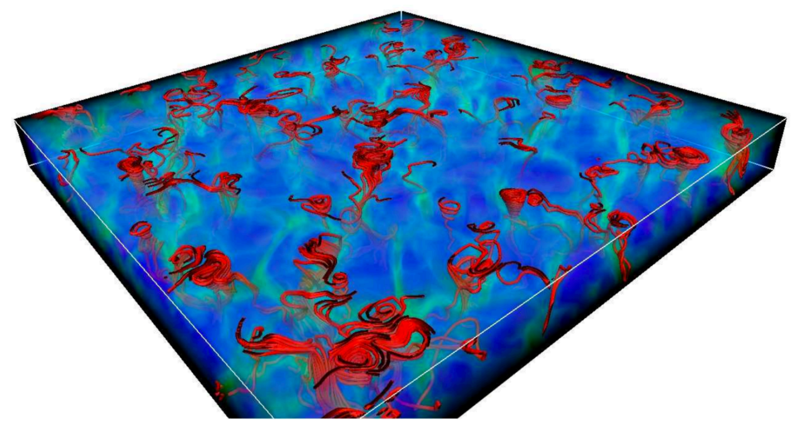
grid resolution of these simulations is 12.5 km.

- Excitation of Acoustic Waves by Vortices in the Quiet Sun (Kitiashvili et al. 2011, ApJL)

VORTEX MOTION (MOTIVATION)



Vertical component of vorticity ωz at the visible solar surface (upper panels) and in the upper photosphere (lower panels). Non-magnetic (left) and magnetic (right) snapshots are shown.



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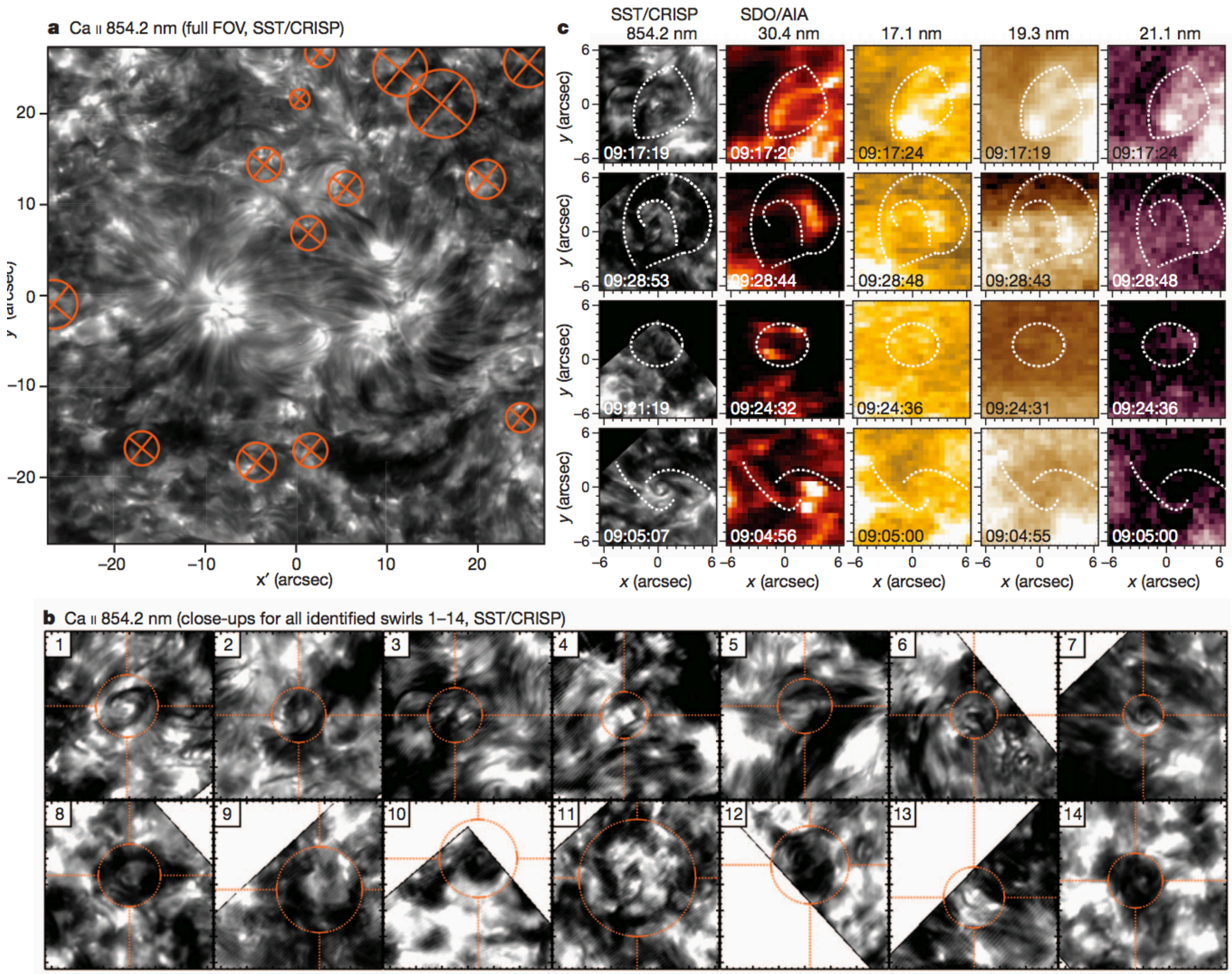


Wedemeyer-Böhm, S et. al. Nature, 486, pp.505-508, 2012

Detected swirl events in the solar observations on 8 May 2011. a) Field of view of SST/CRISP at the centre of the solar disk. All identified swirls marked with crosses and circles on top of an exemplary image in the Ca II 854.2-nm spectral line core. The size of the circles represents the area attributed to the individual swirls.

MAGNETIC TORNADOES AS ENERGY CHANNELS INTO THE SOLAR CORONA

3D-dimensional, radiative MHD codes CO5BOLD and BIFROST

Magnetic tornadoes as energy channels into the solar corona

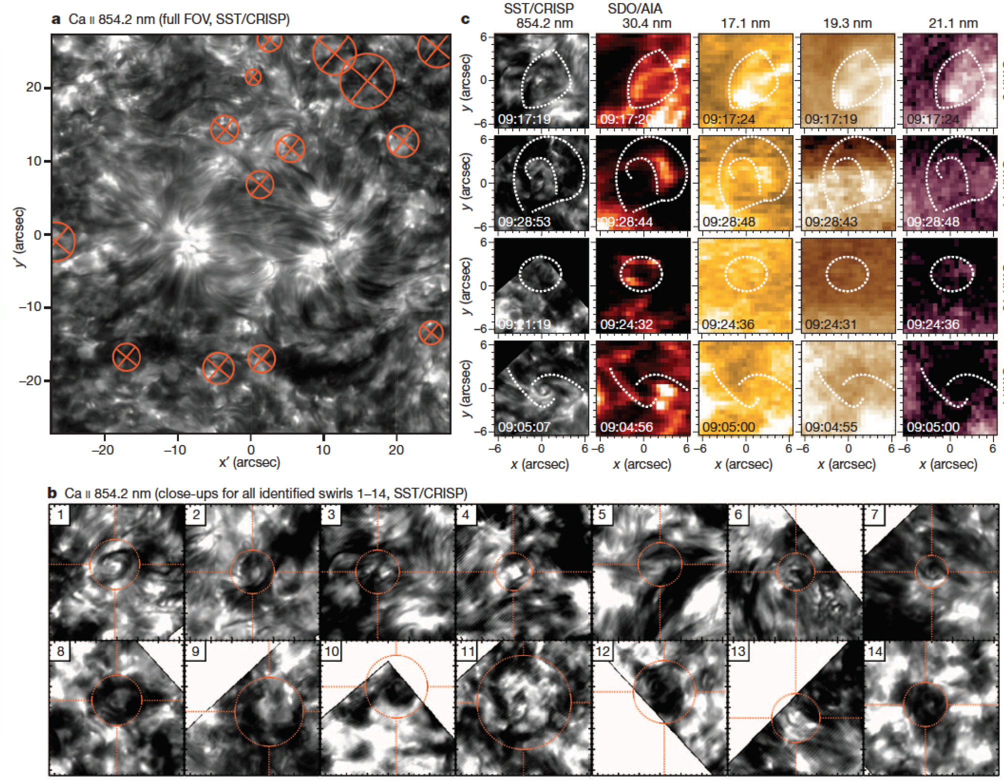
MOVIE 3

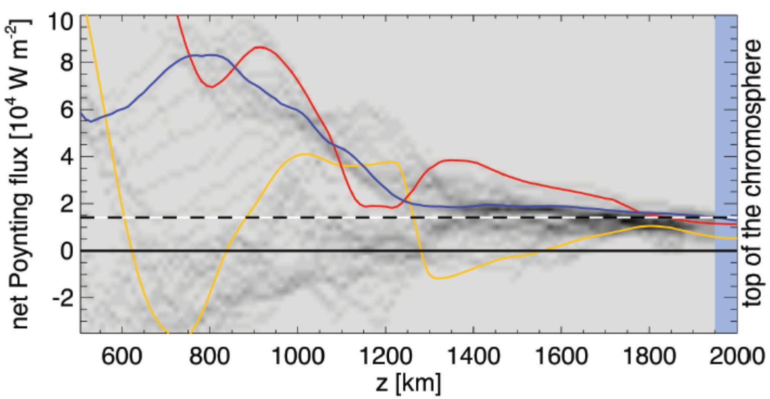
Sven Wedemeyer-Böhm [1,2], Eamon Scullion [1], Oskar Steiner [3], Luc Rouppe van der Voort [1,2], Jaime de la Cruz Rodriguez [4], Viktor Fedun [5], Robert Erdélyi [5]

(2012)

1 Institute of Theoretical Astrophysics, University of Oslo, Norway
2 Center of Mathematics for Applications, University of Oslo, Norway
3 Kiepenheuer Institute for Solar Physics, Freiburg, Germany
4 Department of Physics and Astronomy, Uppsala University, Sweden
5 Solar Physics & Space Plasma Research Centre, Uni. of Sheffield, England (UK)

UiO : Institute of Theoretical Astrophysics
University of Oslo



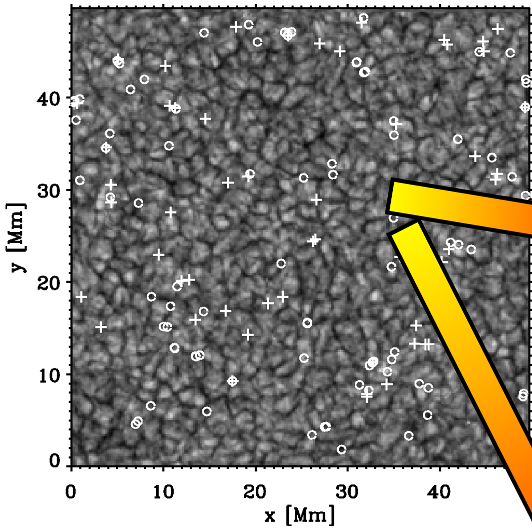


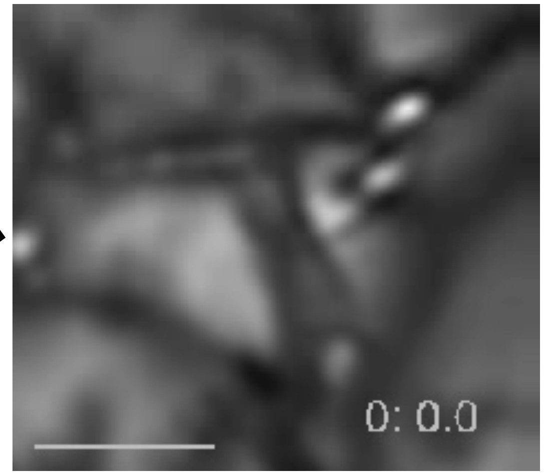
Part of the remaining net flux of 14 kW/m^2 be dissipated in low corona, where it contributes significantly to heating

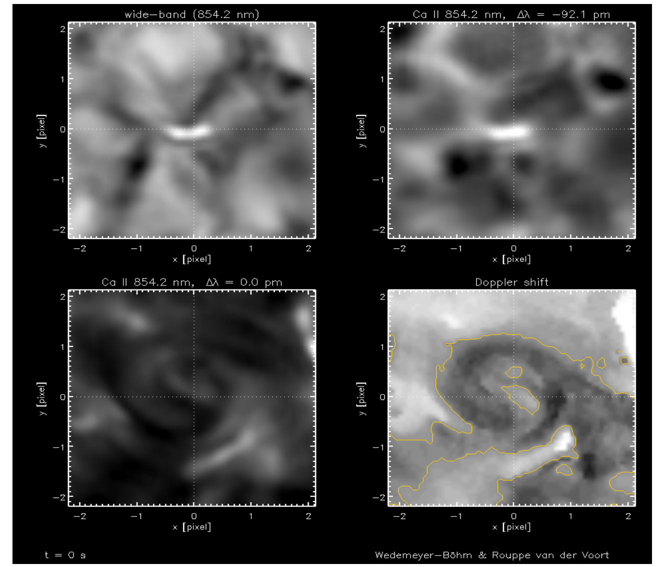
Nature, 2012

VORTEX MOTION (MOTIVATION)

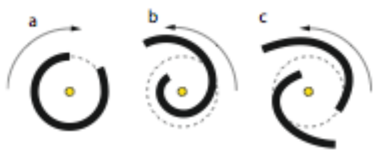
Convectively Driven Vortex Flows in the Sun Bonet et al. (2008), S.Wedemeyer-Böhm and L. Rouppe van der Voort, A&A, 2009

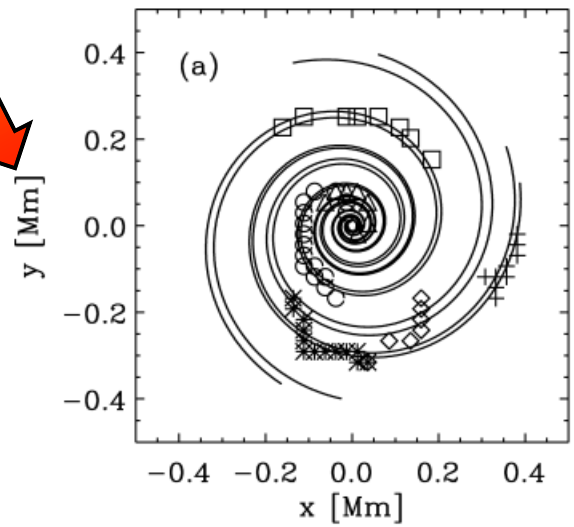






SST observed small scale rotational motion of magnetic bright points, counterclockwise (+) and clockwise (o)

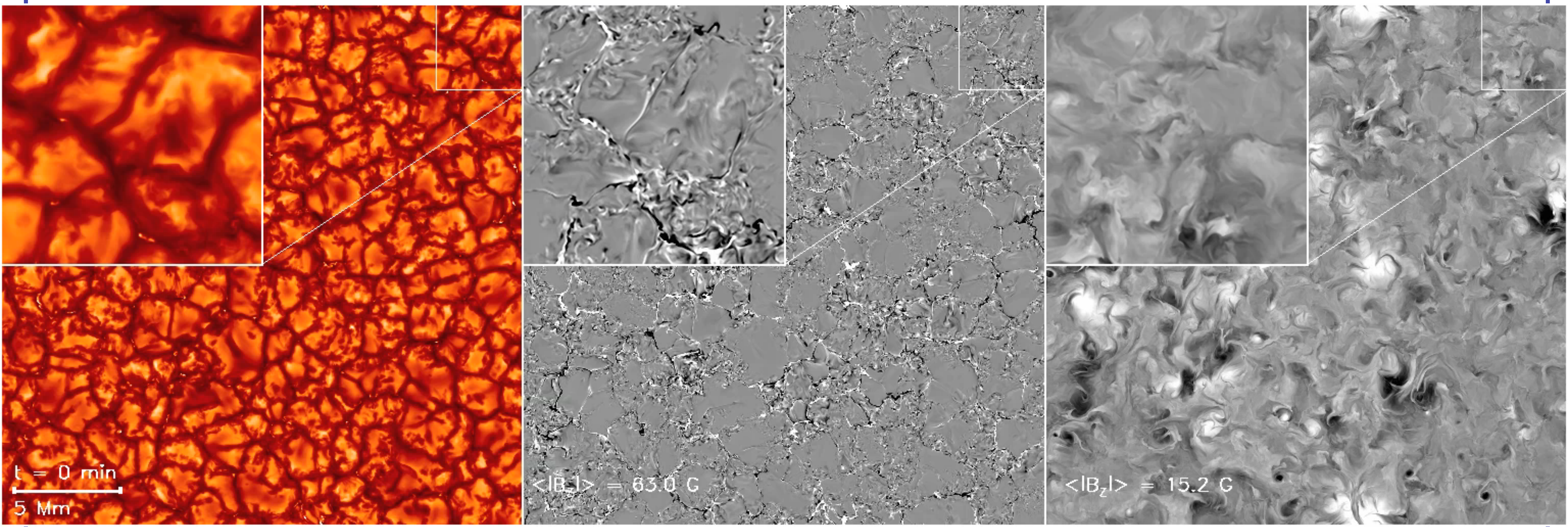




The movies show BPs swirling around intergranular points where several dark lanes converge. These motions are reminiscent of the bathtub vortex flows.

Torsional Alfvén waves may be generated all over the photosphere!

VORTEX MOTION IN NUMERICAL SIMULATION



Courtesy to Mattias Rempel

VORTEX IDENTIFICATION

Questions we to Answer

– Are vortex motions in the solar atmosphere ubiquitous?

– What is their typical lifetime?

– What are their characteristic scales?

– What is the maximum perpendicular velocity, and, how does it relate to the vortex size?

– How does the theory compare with the observations?

– What is the energy flux due to vortical motions in the upper

layers of the atmosphere?

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To answer the above set of questions we need the following information:

- Doppler on the photosphere
- Doppler on the chromosphere
- Magnetic field on the photosphere
- Magnetic field on the chromosphere (IBIS +)
- 3D velocity on the photosphere
- 3D velocity on the chromosphere

VORTEX IDENTIFICATION

We have seen that vortical motions practically appear everywhere in the solar atmosphere.

To support this hypothesis we have analyzed data from several heights in the solar atmosphere.

- Image stabilisation
- The velocity field estimate from intensity images (LCT)
- Describe $\Gamma 1$ and $\Gamma 2$ functions
- Proper Orthonormal Decomposition (POD)
- Covering ellipsoid method for selecting vortices with specific major to minor axis ratios

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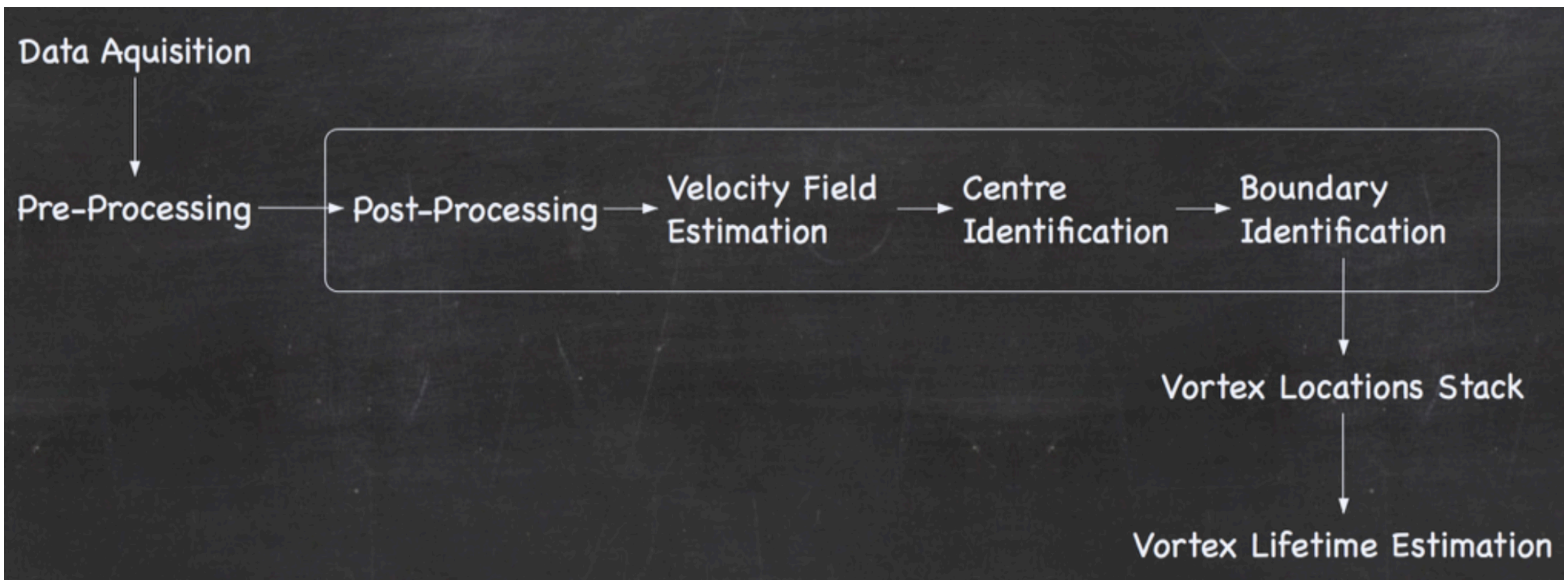


VORTEX IDENTIFICATION

(Histogram Equalization + Blind Deconvolution)

Histogram Equalization

The intensity maps obtained from observations have varying intensity at different times that appears to be due to atmospheric effects, given that the magnitude of the intensity variation is a few standard deviations from the mean, and, the effect is global, i.e. affects almost equally the entire image and disappears in subsequent frames. To counter these effects image histogram equalization was used in the following way:

– First, the expected distribution of intensities is estimated by means of averaging the histogram distributions across all frames. The rationale for this is that the Sun is not expected to change is power emission spectrum during the time of the observation.

– Once the expected intensity distribution has been obtained, histogram equalization is applied to all frames using that distribution as a reference.

This procedure is fast and efficiently removes inter frame flickering, and, improves the numerical stability of the LCT method.

Blind Deconvolution

In image processing, blind deconvolution is a deconvolution technique that permits recovery of the target scene from a single or set of "blurred" images in the presence of a poorly determined.

IDENTIFICATION OF VORTEX MOTION

Original data

Equalized and stabilized data

VORTEX IDENTIFICATION

(Proper Orthonormal Decomposition)

Proper Orthonormal Decomposition (POD) +

Covering ellipsoid method for selecting vortices with specific major to minor axis ratios

Γ1 and Γ2 **functions identify the locations of the centre and boundary of the vortex on the basis of the velocity field. The POD computed for the measured velocity fields and shows how spatial modes are responsible for most of the fluctuations observed in the vicinity of the location of the mean vortex centre.**

Graftieaux, L., Michard, M., & Grosjean, N. 2001, Measurement Science and Technology, 12, 1422

- Gamma 1
  - Absolute value achieves maximum at vortex centre.

$$\Gamma_1(\mathbf{x}_p) = \frac{1}{|S|}\sum_S \frac{((\mathbf{x}_m - \mathbf{x}_p) \times \mathbf{v}_m) \cdot \mathbf{1}_z}{||\mathbf{x}_m - \mathbf{x}_p||_2 \cdot ||\mathbf{v}_m||_2}$$

where $S = \{\mathbf{x} : ||\mathbf{x} - \mathbf{x}_p||_2 \leq R\}$ is a disk of radius R about the point $\mathbf{x}_p$, $||\cdot||_2$ is the Euclidean norm, $\mathbf{1}_z$ is a unit vector normal to the plane and $A(\cdot)$ is the area. Γ_1 defines a scalar field and its magnitude achieves a maximum at 1. Graftieaux et al. (2001) shows that this function achieves this maximum when $\mathbf{x}_p$ is at the center of an axisymmetric vortex.

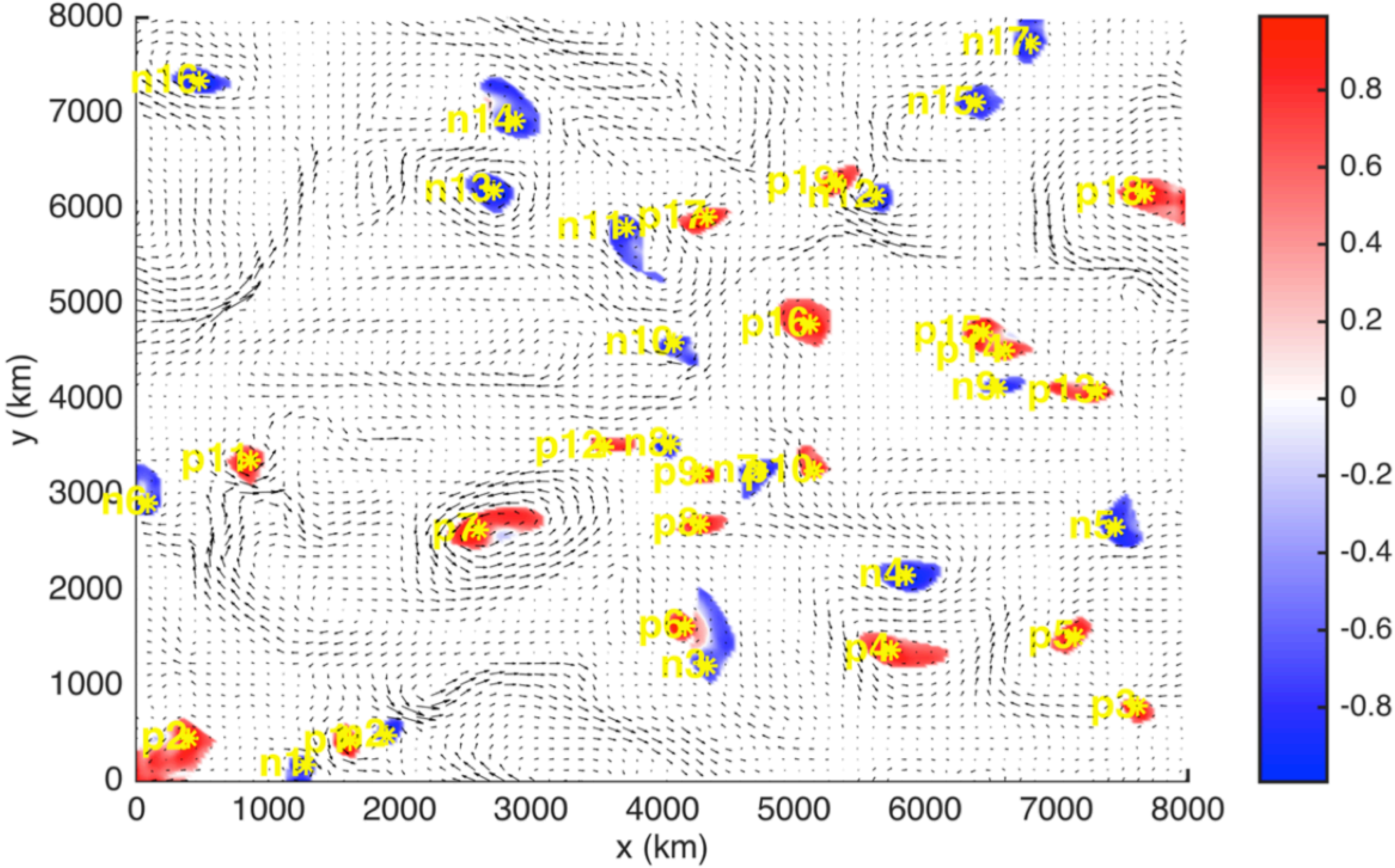
- Gamma 2
  - Galilean invariant.
  - Vortex core at $|\Gamma_2| > 2/\pi$

$$\Gamma_2(\mathbf{x}_p) = \frac{1}{N}\sum_S \frac{((\mathbf{x}_m - \mathbf{x}_p) \times (\mathbf{v}_m - \bar{\mathbf{v}}_p)) \cdot \mathbf{1}_z}{||\mathbf{x}_m - \mathbf{x}_p||_2 \cdot ||\mathbf{v}_m - \bar{\mathbf{v}}_p||_2}$$

where $\bar{\mathbf{v}}_p$ is the mean velocity in the neighborhood of the point $\mathbf{x}_p$. It is shown in Graftieaux et al. (2001) that in the inner core of a vortex the magnitude of Γ_2 is larger than $2/\pi$.

VORTEX IDENTIFICATION

VORTEX IDENTIFICATION



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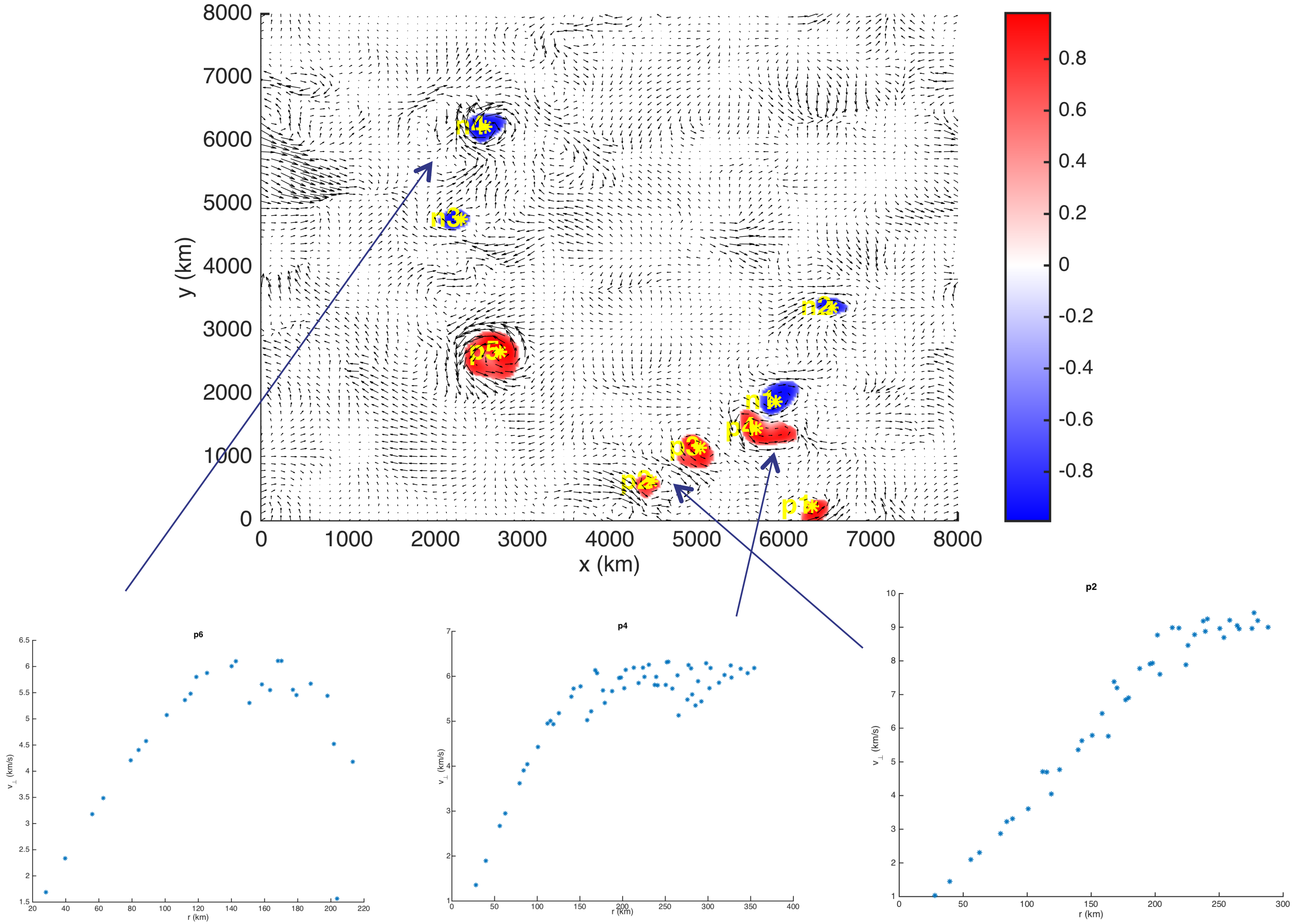


VORTEX MOTION

We theoretically investigate the of large-scale vortex structures of dispersionless Alfven waves. It is shown that Alfven waves can propagate in the form of Alfven vortices of finite characteristic radius and characterised by magnetic flux ropes carrying orbital angular momentum. (*Physics of plasmas, Onischenko, et al. 2015*)

$$\frac{v_\phi}{v_A} = \frac{1}{v_A B_0}\frac{\partial\varphi}{\partial r} = \alpha\frac{r}{r_0}\left(1-\frac{r^2}{r_0^2}\right)\exp\left(-\frac{r^2}{r_0^2}\right)\cos(l\phi),$$

$$\frac{v_r}{v_A} = -\frac{1}{v_A B_0 r}\frac{\partial\varphi}{\partial\phi} = \alpha l\frac{r}{2r_0}\exp\left(-\frac{r^2}{r_0^2}\right)\sin(l\phi).$$

From the expression $\mathbf{B}_\perp = \nabla A\times\mathbf{e}_z$ we have

$$B_r = \frac{1}{r}\frac{\partial A}{\partial\phi} = -B_0\frac{v_r}{v_A},$$

$$B_\phi = -\frac{\partial}{\partial r}A = -B_0\frac{v_\phi}{v_A}.$$

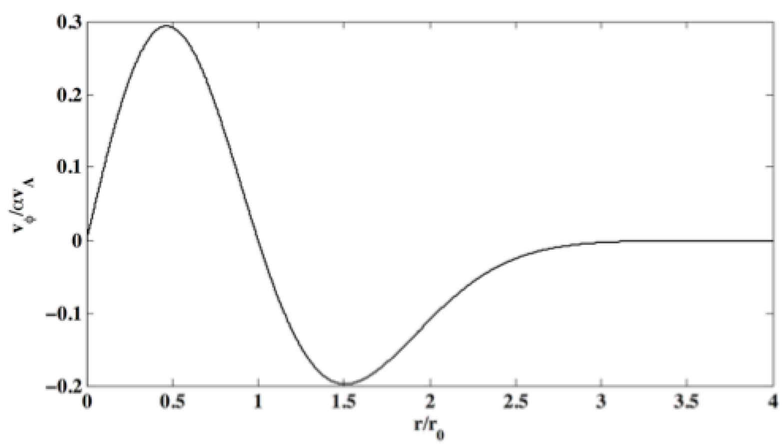


Fig. 1. The normalised value of the toroidal speed v_φ as a function of distance from the centre of vortex r/r_0.

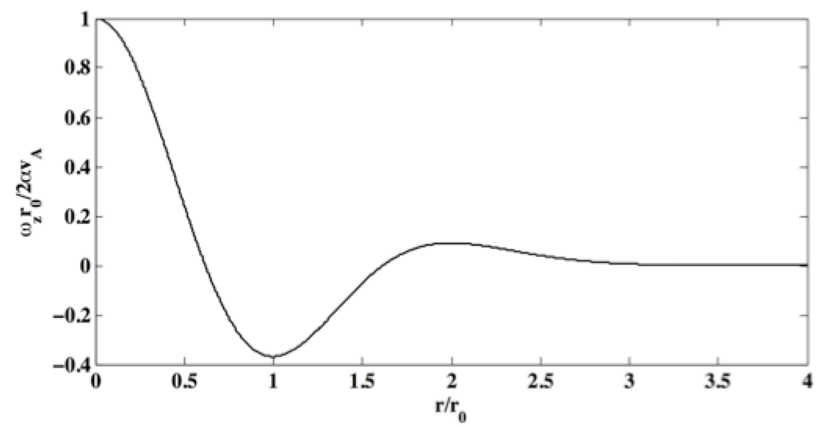
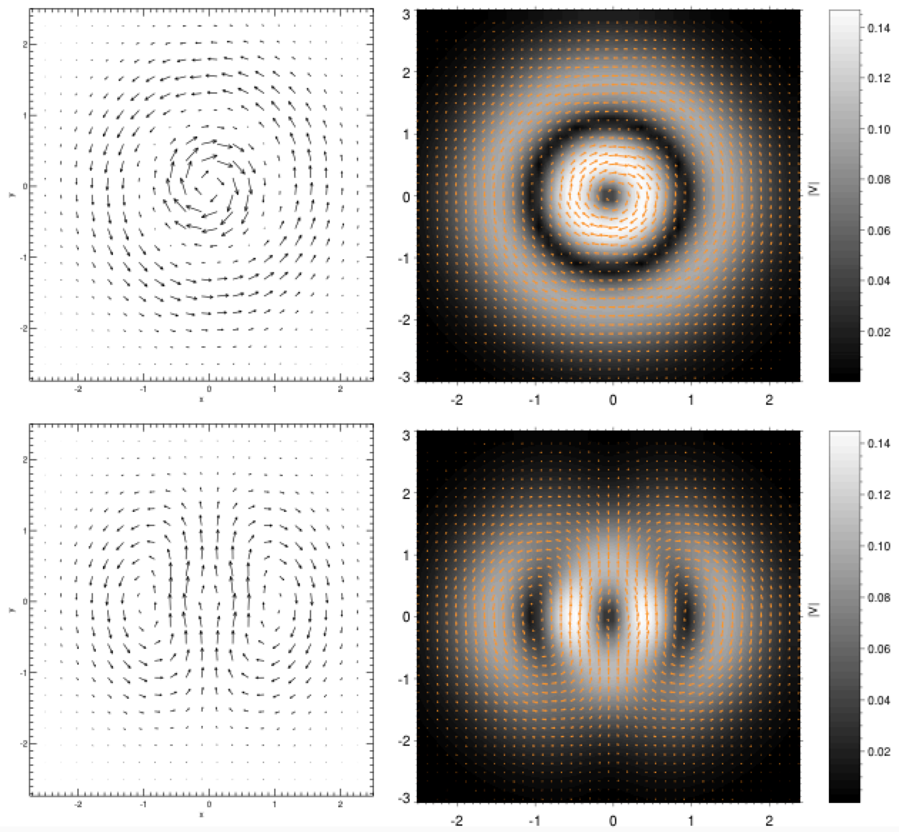


Fig. 3. The normalised value of the vertical vorticity ω_z as a function of distance from the centre of vortex r/r_0.

VORTEX MOTION



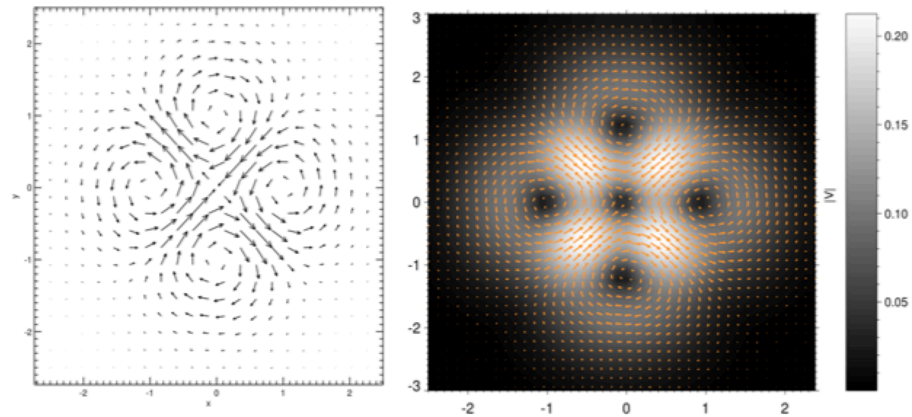
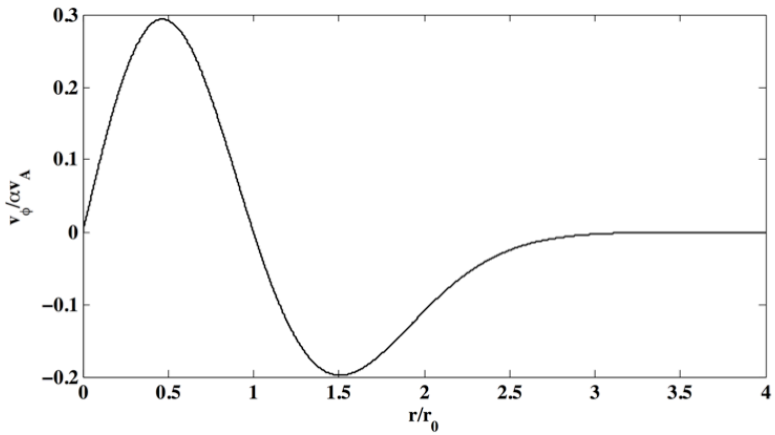


Fig. 5. The horizontal structure of the three different vortex velocity field patterns calculated for l=0, 1 and 2 (from the top to the bottom, correspondingly).

VORTEX MOTION THEORY VS IDENTIFICATION



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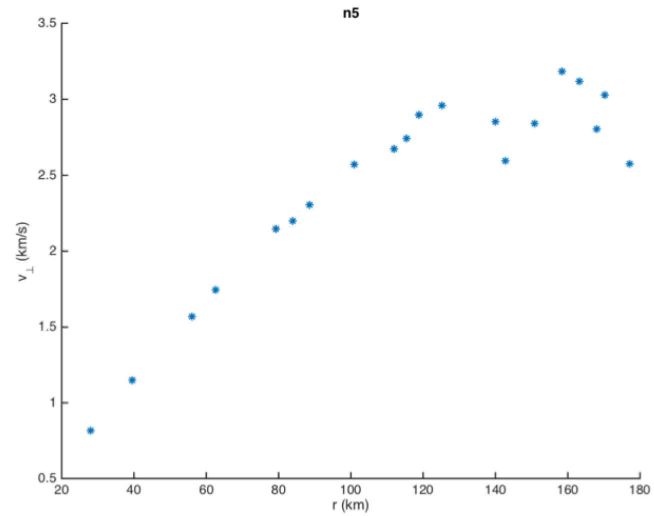


Fig. 2. Perpendicular speed for a vortex as a function of the radius (based on analysis of the observational data).

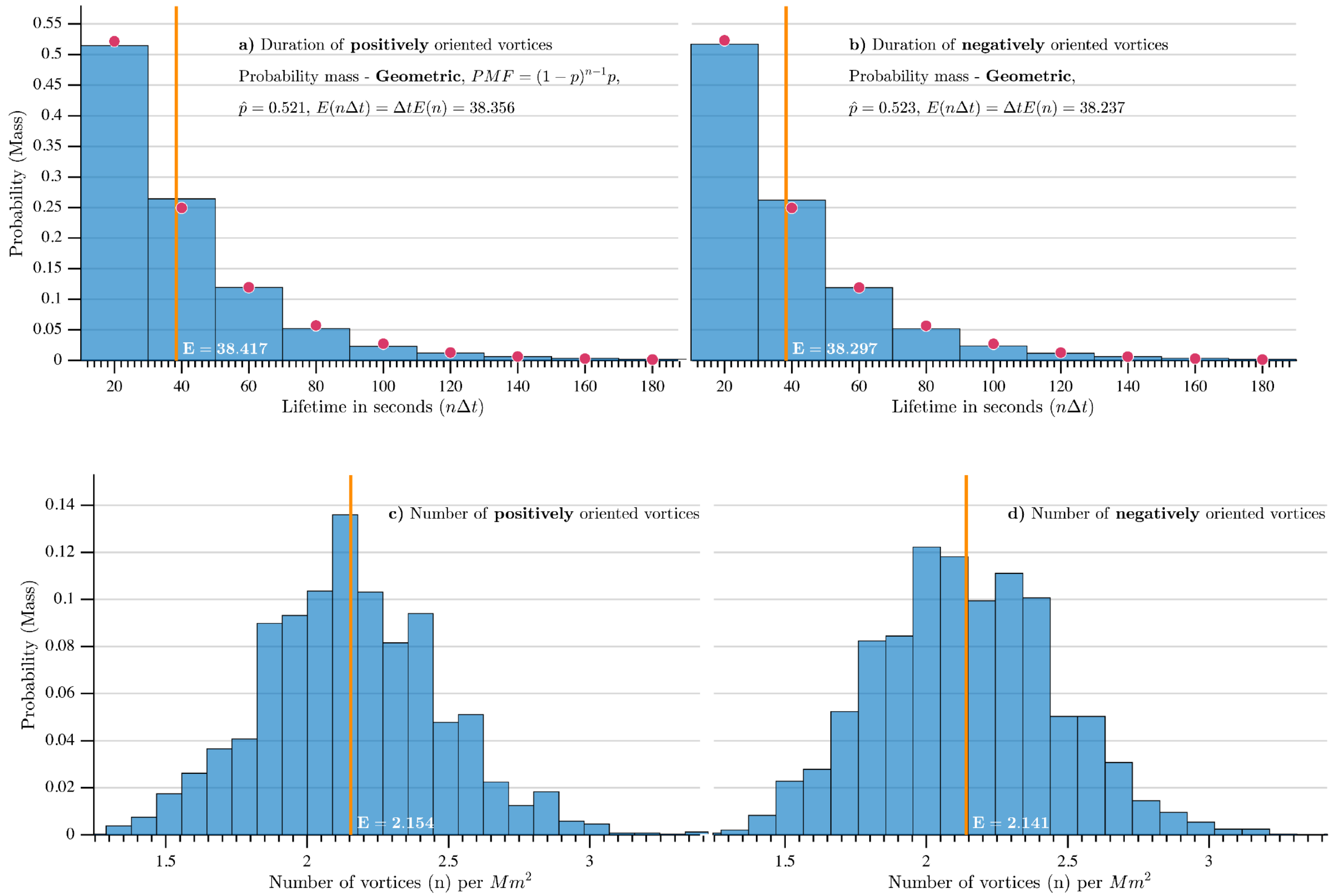
VORTEX IDENTIFICATION (STATISTICS)

dt = 0	Counter Clockwise Vortices				Clockwise Vortices				Total			
	mean	std	max	min	mean	std	max	min	mean	std	max	min
Count	5.424279	2.131367	14	0	5.424279	2.131367	14	0	10.93299	3.200397	25	1
Radius	847.3764	147.9766	1861.916	377.7392	865.009	150.4714	1876.231	373.1657	856.2007	149.4849	1876.231	373.1657
Area	3020109	1498041	14089380	0	3212067	1573786	11953785	0	6232176	2246298	18238536	624962
Area (perc of sun)	4.083436	2.025474	19.05	0	4.342979	2.127888	16.1625	0	8.426415	3.037179	24.66	0.845
vperp	0.614138	0.11874	1.486135	0	0.621397	0.112728	1.426601	0	0.617767	0.115825	1.486135	0
vortex center doppler	1.799593	0.956759	8.388774	-2.63561	1.80879	0.92541	7.480769	-4.07653	1.804191	0.941191	8.388774	-4.07653
mean doppler	1.798122	0.875238	6.728872	-2.53919	1.814187	0.829092	5.71564	-2.09325	1.806155	0.852483	6.728872	-2.53919
max doppler	5.64905	1.889956	19.30752	-0.51177	5.701439	1.795571	19.30752	-0.09487	5.675244	1.843485	19.30752	-0.51177
min doppler	-2.28374	1.870712	3.850047	-12.6906	-2.34188	1.961621	4.442162	-14.3132	-2.31281	1.916854	4.442162	-14.3132
vortex center doppler (mm)	0.013643	0.837262	6.142859	-4.87559	0.019558	0.820177	5.691773	-5.33471	0.0166	0.828737	6.142859	-5.33471
mean doppler (mm)	0.012172	0.74792	4.913446	-4.20339	0.024955	0.703033	3.609077	-4.25645	0.018563	0.725824	4.913446	-4.25645
max doppler (mm)	3.863099	1.800222	17.49995	-2.60211	3.912207	1.719532	17.49639	-1.86223	3.887653	1.760444	17.49995	-2.60211
min doppler (mm)	-4.06969	1.817027	1.988377	-14.3214	-4.13111	1.90061	2.136345	-16.2153	-4.1004	1.859472	2.136345	-16.2153

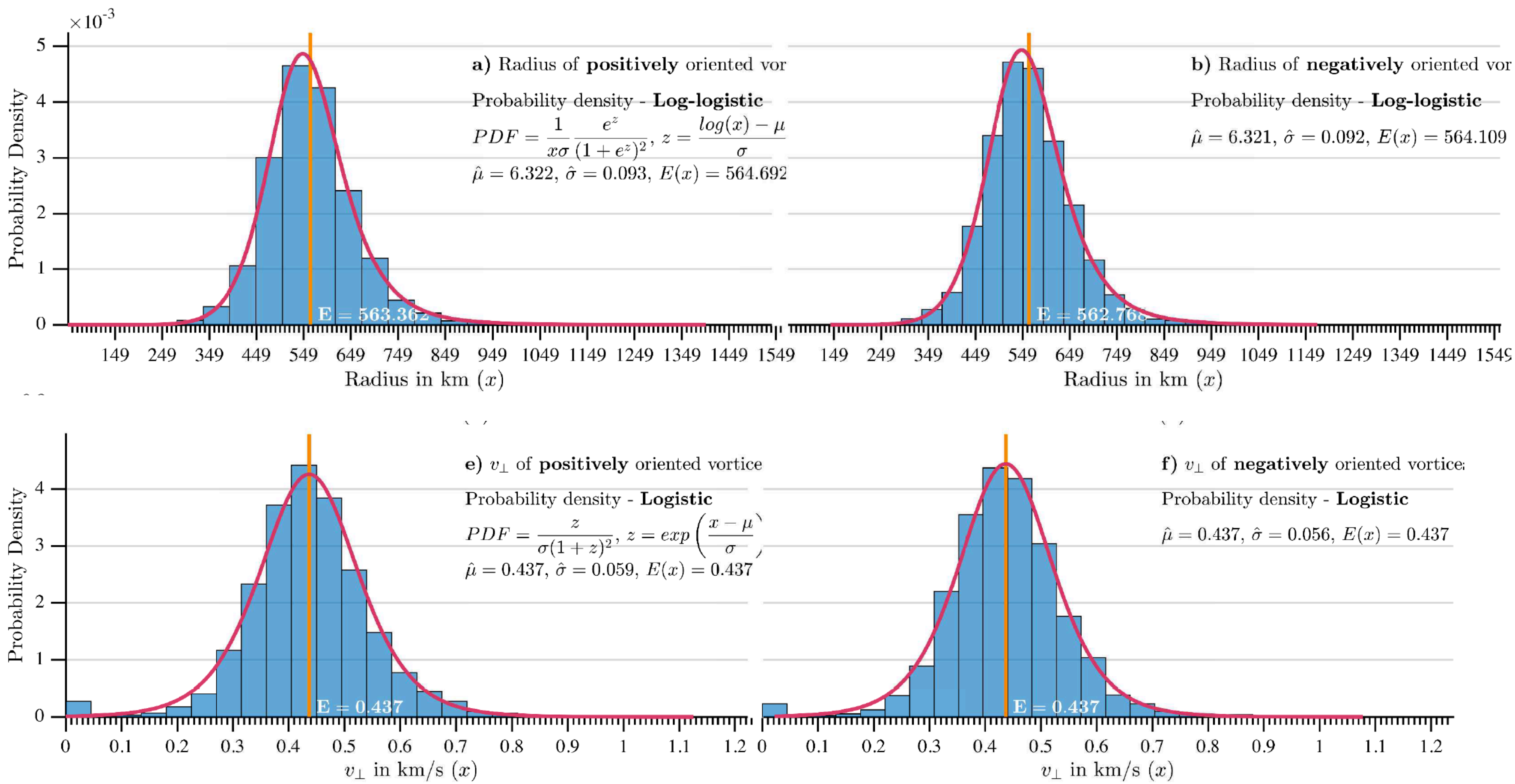
dt = 1	Counter Clockwise Vortices				Clockwise Vortices				Total			
	mean	std	max	min	mean	std	max	min	mean	std	max	min
Count	5.423343	2.13129	14	0	5.423343	2.13129	14	0	10.93268	3.202483	25	1
Radius	847.4572	148.0303	1861.916	377.7392	864.9635	150.5655	1876.231	373.1657	856.2183	149.5552	1876.231	373.1657
Area	3020635	1498997	14089380	0	3211968	1574558	11953785	0	6232602	2248411	18238536	624962
Area (perc of sun)	4.084146	2.026767	19.05	0	4.342844	2.128932	16.1625	0	8.426991	3.040037	24.66	0.845
vperp	0.614174	0.118842	1.486135	0	0.621434	0.11275	1.426601	0	0.617804	0.115889	1.486135	0
vortex center doppler	1.786696	0.960069	10.04101	-3.08245	1.803365	0.93199	6.745468	-3.38298	1.79503	0.946135	10.04101	-3.38298
mean doppler	1.790995	0.876952	7.262777	-2.76006	1.802489	0.834815	5.814801	-3.10658	1.796742	0.85613	7.262777	-3.10658
max doppler	5.634987	1.871423	19.30752	-0.84561	5.684129	1.772287	19.30752	-1.06774	5.659558	1.822626	19.30752	-1.06774
min doppler	-2.29591	1.868665	4.232	-12.6906	-2.34025	1.951297	4.340295	-15.446	-2.31808	1.910485	4.340295	-15.446
vortex center doppler (mm)	0.000556	0.842261	7.717464	-4.72826	0.013992	0.826358	4.94236	-5.12229	0.007274	0.834343	7.717464	-5.12229
mean doppler (mm)	0.004855	0.752464	4.939227	-4.4301	0.013115	0.710355	3.437529	-5.35939	0.008985	0.731696	4.939227	-5.35939
max doppler (mm)	3.848848	1.779221	17.49995	-2.90289	3.894755	1.695278	17.53216	-3.32055	3.871802	1.737842	17.53216	-3.32055
min doppler (mm)	-4.08205	1.817858	2.093911	-14.3214	-4.12963	1.887751	2.196721	-17.2628	-4.10584	1.853217	2.196721	-17.2628

VORTEX IDENTIFICATION (STATISTICS)

Estimates from **magnetoconvection simulation**



VORTEX IDENTIFICATION (STATISTICS, OBSERVATIONS)

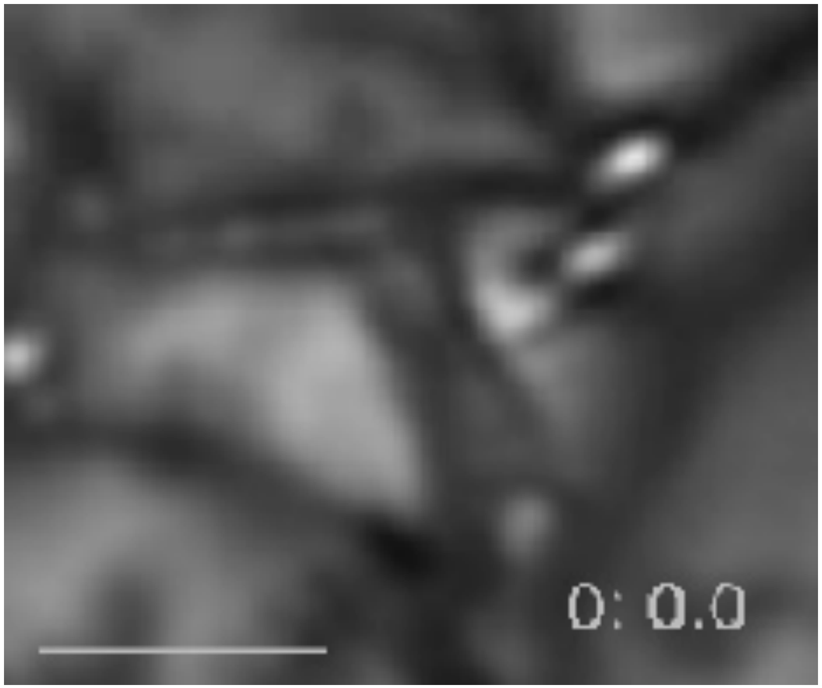


VORTEX IDENTIFICATION

(PRELIMINARILY RESULTS)

- Are vortical motions in the solar atmosphere ubiquitous ? **Yes**
- If they are, where are they located ? **Mostly in the inter-granular lanes**
- Mean number of vortices on the solar photosphere ? **Approx 8.9×10^5**
- Max number of vortices on the solar Photosphere ? **Approx 2.05×10^6**
- What is the total area of vortices on the Sun at any given time and what is the proportion of that area to the solar surface ? **8.42%**
- What are their characteristic scales ? **Typical radius is approx 847.37 km**
- What is the maximum perpendicular velocity ? **Approx 1.486 km/s**
- What is the mean perpendicular velosity ? **Approx 0.613 km/s**

IDENTIFICATION OF VORTEX MOTION



VORTEX MOTION