Probing coronal magnetic field by kink oscillations of coronal loops.

Sergey Anfinogentov[1]

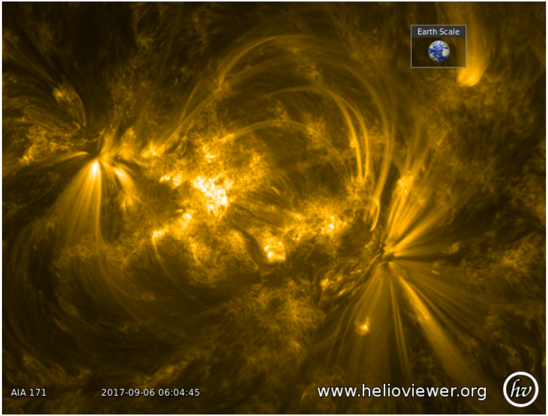
[1]Institute of Solar-Terrestrial physics, Irkutsk, Russia

ISSI team meeting

ISSI Bern, 3 – 7 October 2022

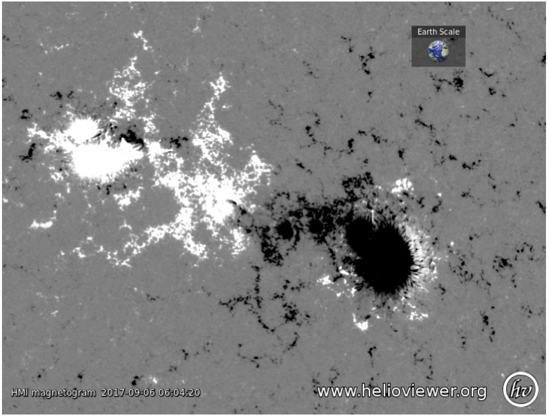
Coronal loops

The basic elements of the solar corona

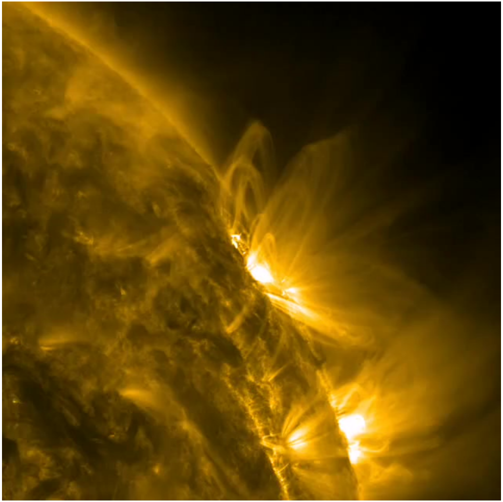


Coronal loops

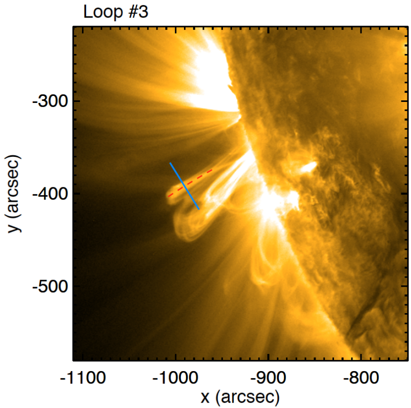
The basic elements of the solar corona

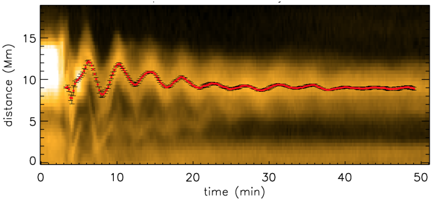


Kink oscillations excited by an eruption



Time-distance plots

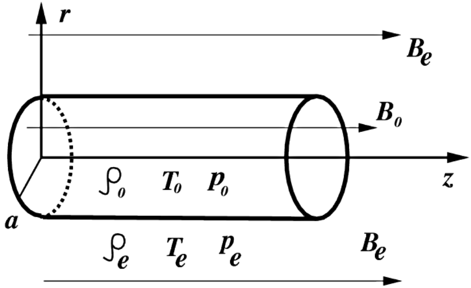




A straight magnetic cyllinder[1]

as the model of a coronal loop

- Natural modes are known
- They are seismologically sensitive



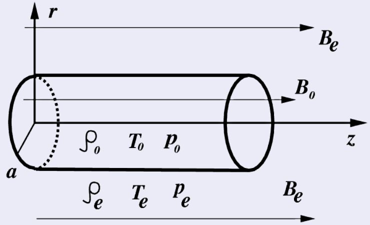
(Sketch from Nakariakov and Verwichte, 2005)

[1] Zaitsev and Stepanov (1975), Edwin and Roberts (1981, 1983)

Kink mode of the magnetic cylinder [2]

Magnetic cylinder model

- Natural modes are known
- Sensitive to the magnetic field



(Sketch from Nakariakov and Verwichte, 2005)

Phase speed ($\beta << 1$)

$$\frac{\omega}{k} = c_\mathrm{k}$$

$$c_\mathrm{k} = \sqrt{\frac{2}{1+\rho_\mathrm{e}/\rho_0}} c_\mathrm{A}$$

$$c_\mathrm{A} = \frac{B}{\sqrt{\mu_0 \rho_0}}$$

Oscillation period (standing wave)

$$P = \frac{2L}{n c_\mathrm{k}}$$

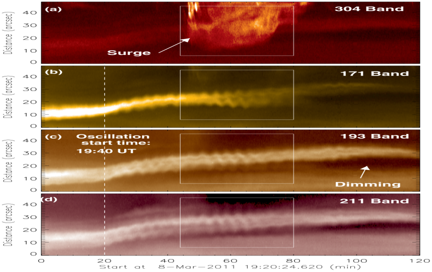
Magnetic field inversion

$$B = \frac{\sqrt{2\mu_0} L}{nP} \sqrt{\rho_0 (1 + \rho_\mathrm{e}/\rho_0)}$$

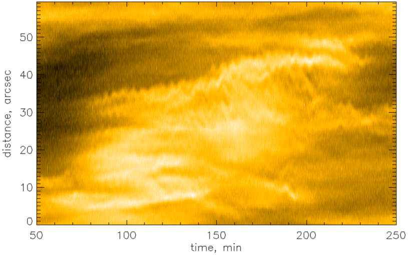
[2] Zaitsev and Stepanov (1975), Edwin and Roberts (1981, 1983)

Decay-less kink oscillations

First observations

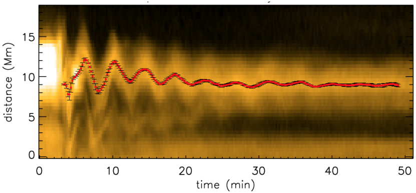


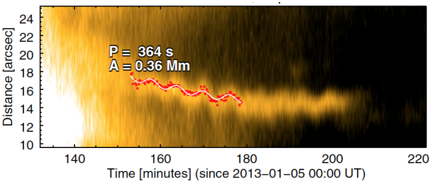
Firstly discovered by [Wang et al., 2012]



Can last for several hours in quiet active regions[Anfinogentov et al., 2013] и can be observed in any active region at any time [Anfinogentov et al., 2015]

Decaying vs decay-less oscillations





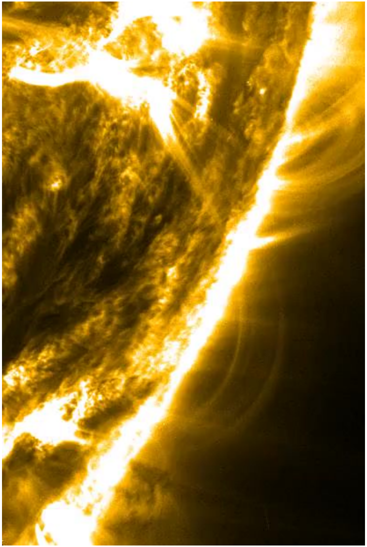
Decaying vs decay-less oscillations

	Decaying[3]	Decay-less[4]
Displacement amplitude	~ 5 Mm	~ 0.2 Mm
Velocity amplitude	~ 50 km$\cdot\mathrm{s}^{-1}$	~ 2 km$\cdot\mathrm{s}^{-1}$
Existence time	3 – 4 cycles	up to several hours
Association with flares	yes	no
Appearance	~ 50 events a year	ubiquitous

[3] [Goddard et al., 2016]

[4] [Nisticò et al., 2014, Anfinogentov et al., 2013, Anfinogentov et al., 2015]

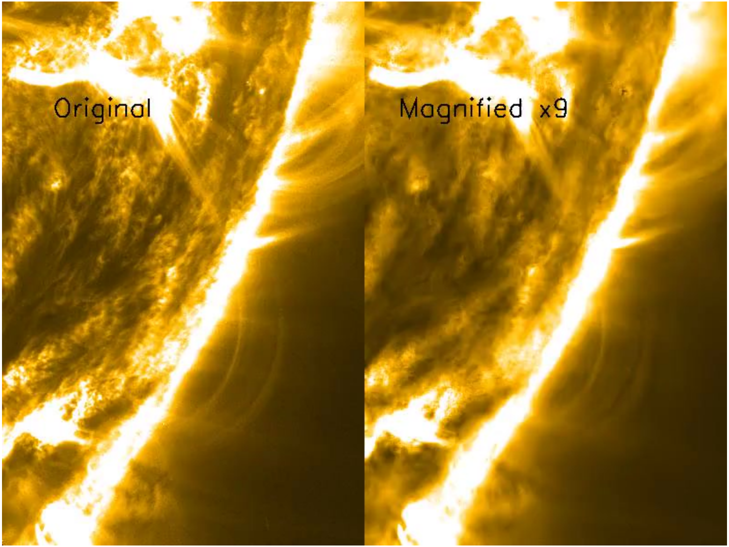
Low-amplitude — large problem



Motion magnification x30

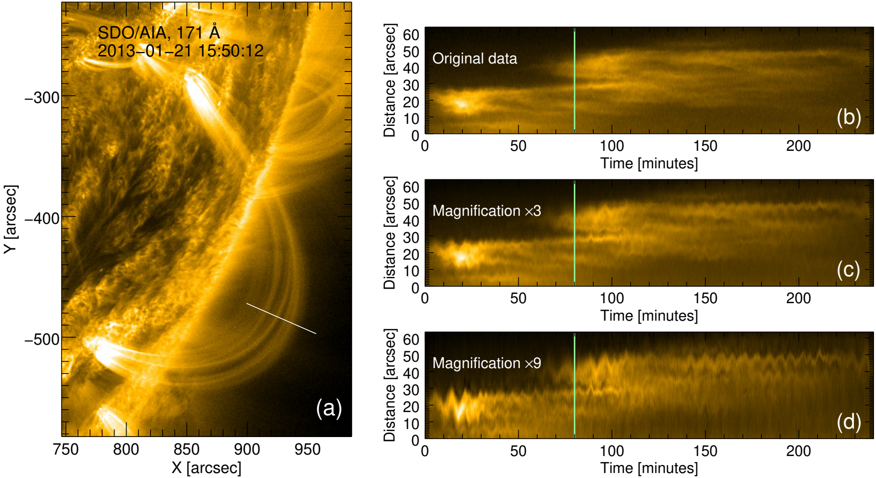
Lamppost and the wind

SDO/AIA data after motion magnification



Detection of law-amplitude motions

Motion magnification



Problem statement

Goal: obtaining Coronal magnetic field measurements with spatial resolution.

- Observing decay-less oscillations
- Measuring Alfvén speed for several loops
- Measuring plasma density in the loops
- Estimate magnetic field strength
- Combining all measurements into a coronal seismogram
- Accounting for uncertainties

Alfvén speed

Kink speed

$C_{\mathrm{k}} = \frac{2L}{P}$

Internal Alfvén speed

$C_{\mathrm{A0}} = C_{\mathrm{k}}/\sqrt{2/(1+\eta)}$

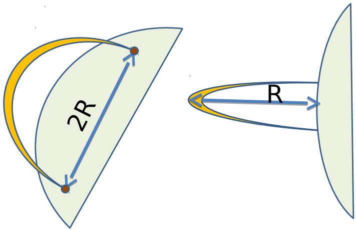
External Alfvén speed

$C_{\mathrm{Ae}} = C_{\mathrm{A0}}/\sqrt{\eta}$

1. P — Oscillation period
2. L — Loop length
3. Transversal density profile
    1. $\eta = \rho_{\mathrm{e}}/\rho_0$ — density contrast
    2. ρ_0, ρ_{e} — densities inside and outside of the loop

Loop length

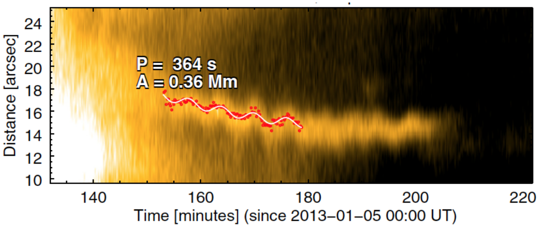
1. **Circular shape assumption** [5]
   - Distance between the footpoints (on disk)
   - The height of the loop (on limb)
2. Stereoscopic observations (STEREO + SDO) [6]
3. Based on magnetic field extrapolation



[5] [Anfinogentov et al., 2015]
[6] [Anfinogentov et al., 2013]

Oscillation period

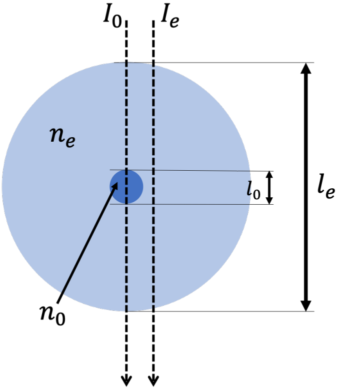
1. Make time-distance plot
2. Measure loop position by fitting its brightness profile
3. Estimate oscillation period and corresponding uncertanty[7]



[7] см. SoBAT MCMC код https://github.com/Sergey-Anfinogentov/SoBAT

Density contrast estimation

Model



l_0 – loop minor diameter
l_e – background plasma spatial scale
n_0 – number density inside the loop
n_e – background plasma density
I_e – Loop intensity
I_e – background intensity
$\eta = n_e/n_0$, $n_e = \eta n_0$

$$I_\mathrm{e} = G(\lambda, T_e) l_\mathrm{e} (\eta n_0)^2$$

$$I_0 = G(\lambda, T_0) \left[(l_\mathrm{e} - l_0)(\eta n_0)^2 + l_0 n_0^2 \right]$$

Density contrast estimation

normalization

- We measure only density contrast and ignore actial values of n_0 и n_e at this step
  - $G(\lambda, T) = 1$
  - $l_0 = 1$

Modeled inensities

$$I_\mathrm{e} = l_\mathrm{e}(\eta n_0)^2$$

$$I_0 = (l_\mathrm{e} - 1)(\eta n_0)^2 + n_0^2$$

Attention!

$$\eta = n_e/n_0 \neq \sqrt{I_e/I_0}$$

Estimation of the density contrast

Bayesian inference

Posterior distribution

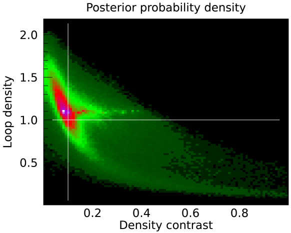
$$P(\mathfrak{I}_0, \mathfrak{I}_\mathrm{e}|\theta) \sim \frac{1}{2\pi\sigma_\mathrm{e}\sigma_0} \exp \frac{-\left[\mathfrak{I}_\mathrm{e} - I_\mathrm{e}(\theta)\right]^2}{2\sigma_\mathrm{e}^2} \exp \frac{-\left[\mathfrak{I}_0 - I_0(\theta)\right]^2}{2\sigma_0^2} P(\theta)$$

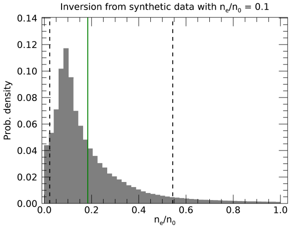
$\theta = [n_0, \eta, l_\mathrm{e}]$ – free model parameters
$\mathfrak{I}_0$, $\mathfrak{I}_\mathrm{e}$ – observed intensities
σ_0, σ_e – measurment errors

Density contrast estimation

Test on artificial data

- Model parameters
  - $n_0 = 1$
  - $\eta = 0.1$
  - $l_e = 100$
- Modeled intensities
  - $I_0 = 2.2$
  - $l_e = 1.0$

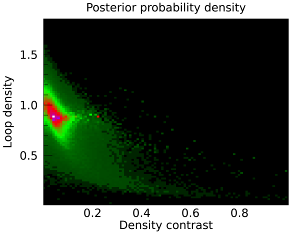


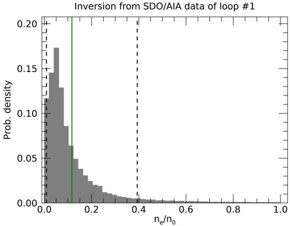


Density contrast estimation

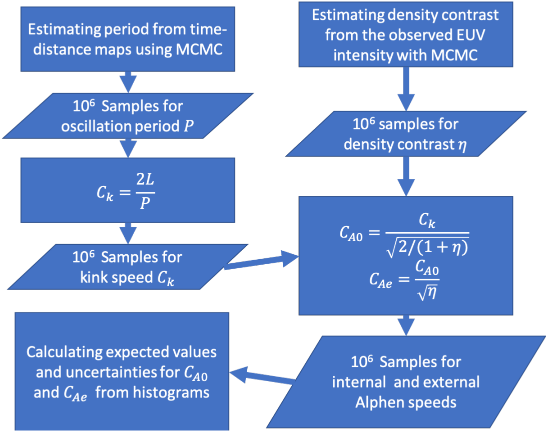
Real data

- Nrmalised intencities
  - $I_0 = 1.0$
  - $l_e = 0.23$
- Inference results
  - $n_0 = 0.8$
  - $\eta = 0.05$



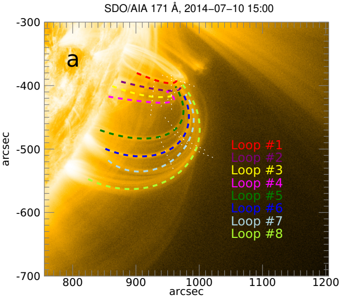


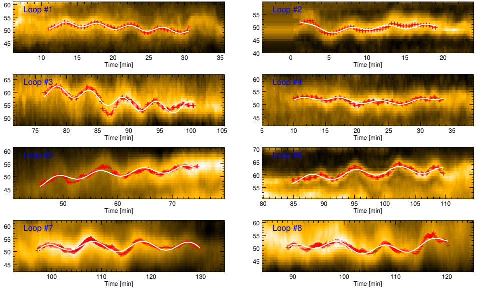
Estimating uncertanties using MCMC



AR 12107

SDO/AIA 171 Å





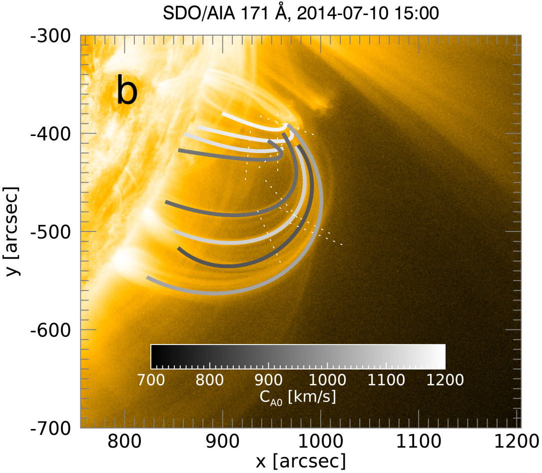
AR 12107

Measurment results

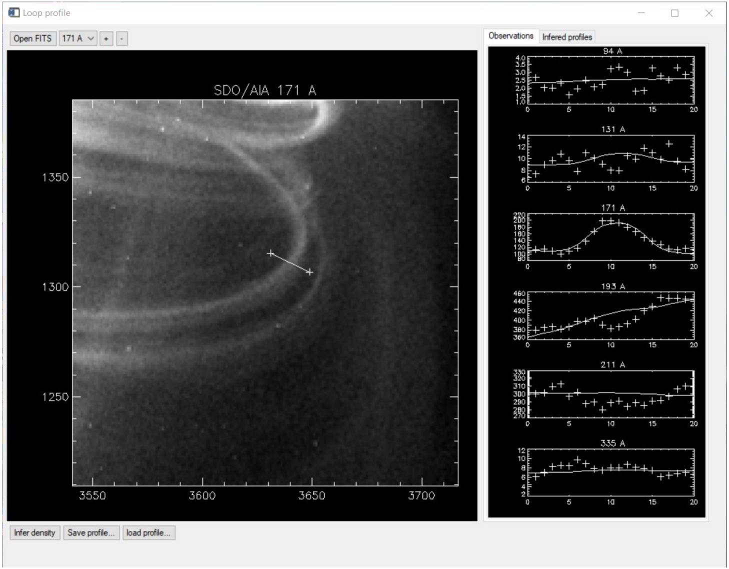
Loop No	Loop length [Mm]	Slit width [px]	Period (s)	Intensity contrast	Density contrast	Kink speed [km/s]	C_{A0} [km/s]	C_{Ae} [km/s]
1	224	1	$276^{+2.8}_{-2.5}$	0.23	$0.04^{+0.35}_{-0.03}$	1622^{+15}_{-17}	1173^{+182}_{-23}	4313^{+7935}_{-2156}
2	231	5	334^{+40}_{-49}	0.46	$0.07^{+0.40}_{-0.05}$	1395^{+226}_{-163}	942^{+338}_{-35}	2765^{+4221}_{-1076}
3	244	11	$321^{+11}_{-7.8}$	0.66	$0.11^{+0.52}_{-0.04}$	1525^{+38}_{-52}	1140^{+240}_{-38}	2122^{+2156}_{-384}
4	235	5	382^{+18}_{-15}	0.70	$0.12^{+0.57}_{-0.04}$	1228^{+49}_{-58}	927^{+218}_{-43}	1549^{+1514}_{-184}
5	292	28	475^{+10}_{-10}	0.50	$0.08^{+0.42}_{-0.06}$	1229^{+26}_{-25}	903^{+161}_{-27}	1974^{+3578}_{-466}
6	329	5	435^{+12}_{-11}	0.43	$0.07^{+0.43}_{-0.05}$	1512^{+39}_{-42}	1110^{+201}_{-38}	2624^{+5352}_{-769}
7	343	15	$580^{+6.7}_{-6.6}$	0.42	$0.06^{+0.43}_{-0.04}$	1184^{+14}_{-14}	866^{+155}_{-21}	1948^{+4051}_{-489}
8	391	13	$547^{+9.0}_{-8.5}$	0.26	$0.04^{+0.37}_{-0.03}$	1429^{+22}_{-23}	1030^{+174}_{-19}	3353^{+6682}_{-1478}

Coronal seismogram

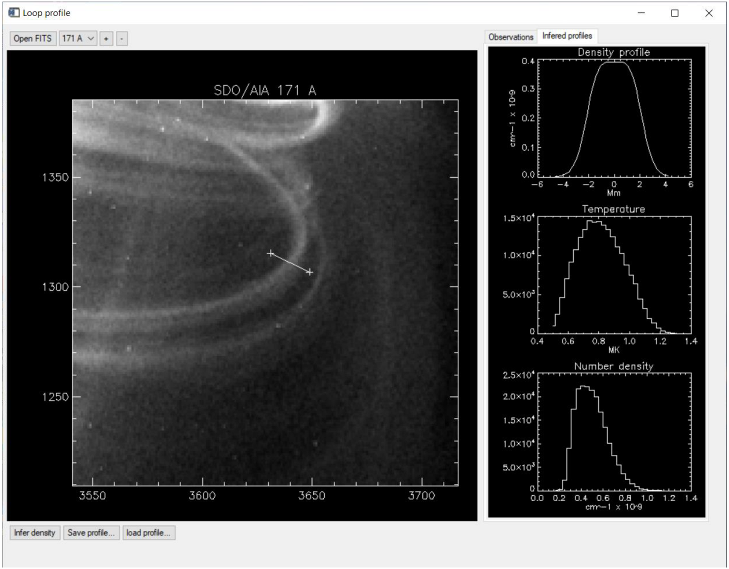
NOAA 12107, 2014-07-10, SDO/AIA 171 Å



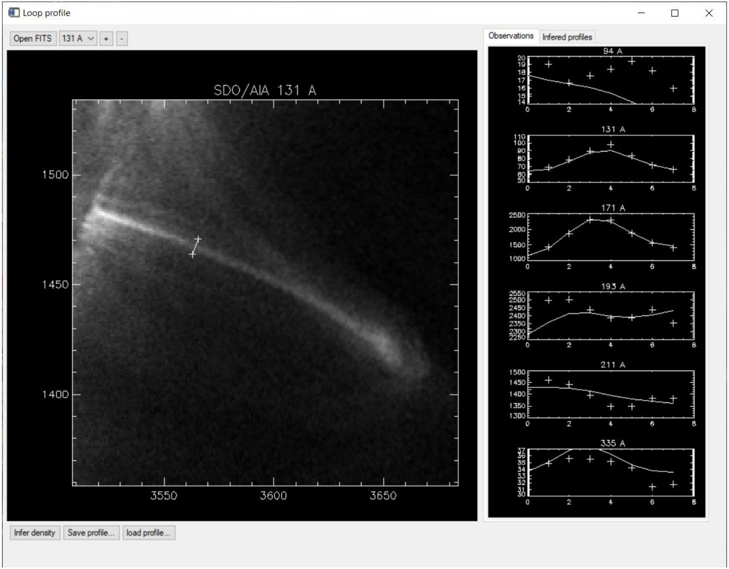
Inferring density profile



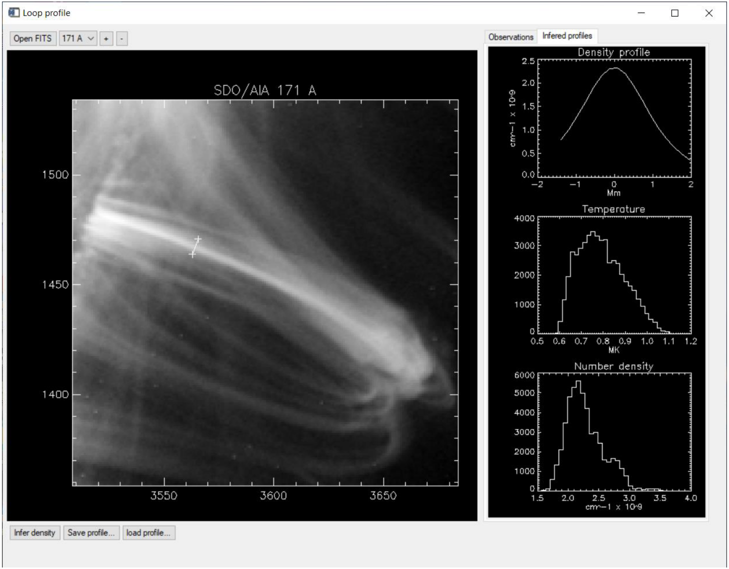
Inferring density profile



Inferring density profiles



Inferring density profile



Topics to discuss

MHD seismology may provide absolute value of the magnetic field "averaged" along a coronal loop.
How can we incorporate this information into self-consistent models of active regions?

Topics to discuss

Coronal loops seen in EUV trace the magnetic field lines.
Can we incorporate this information into self-consistent models of active regions?

Thank you for your attention!

This study was supported by Russian Scientific Foundation under project No 21-12-00195.

References

Anfinogentov, S., Nisticò, G., and Nakariakov, V. M. (2013).
Decay-less kink oscillations in coronal loops.
A&A, 560:A107.

Anfinogentov, S. A., Nakariakov, V. M., and Nisticò, G. (2015).
Decayless low-amplitude kink oscillations: a common phenomenon in the solar corona?
A&A, 583:A136.

Goddard, C. R., Nisticò, G., Nakariakov, V. M., and Zimovets, I. V. (2016).
A statistical study of decaying kink oscillations detected using SDO/AIA.
A&A, 585:A137.

Nisticò, G., Anfinogentov, S., and Nakariakov, V. M. (2014).