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Spectroscopic observations of decayless kink oscillations in coronal loops and sausage oscillations in flare loops

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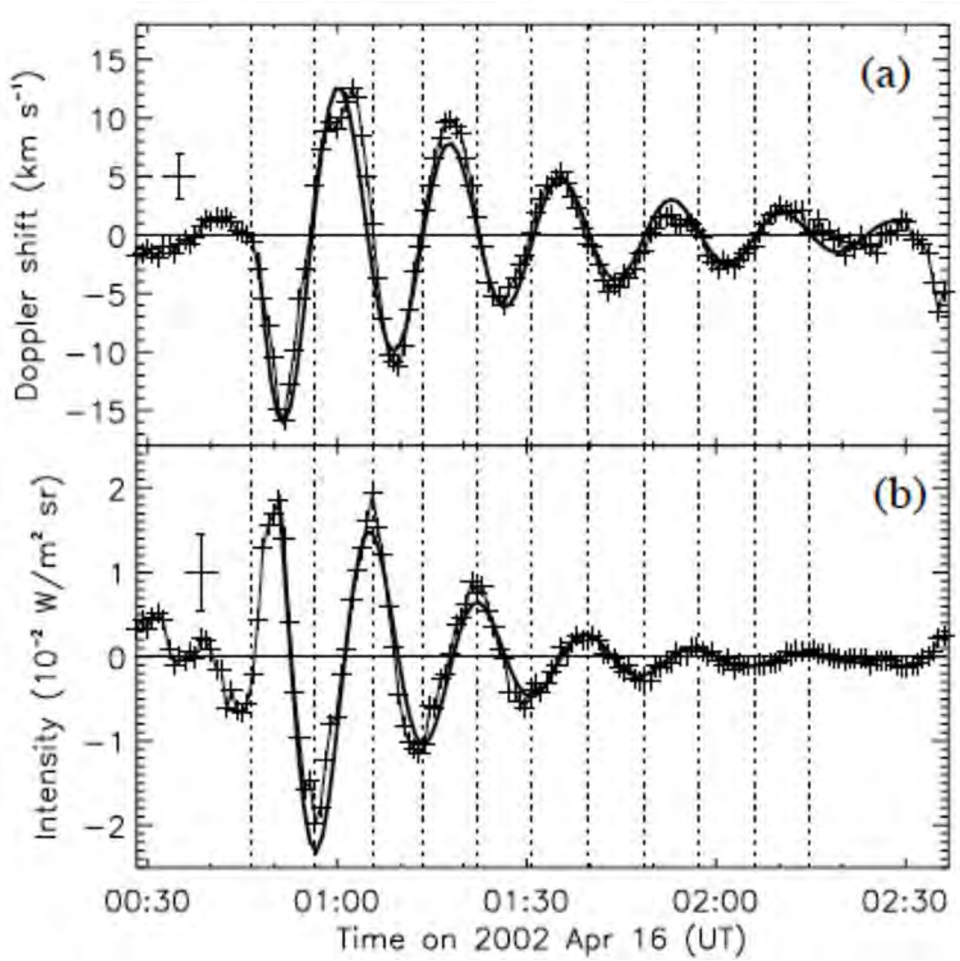
Decaying oscillations and the π/2 phase shift between I & v

- Most reported oscillations show clear decaying. We focus on two types of decayless/persistent oscillations here.

- A π/2 phase shift between intensity and Doppler shift oscillations is often believed to be a signature of slow mode standing wave. We find that similar phase shift may also exist in the cases of kink or sausage mode.



Wang et al. 2003, A&A

Decayless (without significant damping) Doppler shift oscillations in coronal loops

Persistent Doppler Shift Oscillation Events Observed by EIS from February to April in 2007

id	Date	Time	Y	Ri	Rv	Rw	Ra	Pi	Piun	Pv	Pvun	Ai	Av	N	Nerr	Type, Location
1	20070201	013212	351	1.07	0.44	0.30	0.46	10.7	2.44	9.82	2.05	3.89	1.65	9.23	0.04	I, loop leg
2	20070202	004912	245	0.89	0.49	0.51	0.65	7.57	3.19	10.7	4.79	2.36	1.45	9.25	0.04	I, loop leg
3	20070203	005642	193	1.14	0.59	0.56	0.63	8.77	3.00	7.57	2.44	2.71	1.60	9.22	0.04	I, loop leg
4	20070220	175013	296	4.57	2.79	2.33	2.60	11.6	2.04	12.7	2.45	14.0	8.47	9.65	0.13	I, loop leg
5	20070221	021812	310	3.45	1.62	1.33	3.12	10.7	2.90	9.82	2.05	11.8	5.19	9.32	0.17	I, loop leg
6	20070326	150012	168	0.87	0.48	0.48	0.51	8.26	1.88	9.82	2.05	2.53	1.45	9.21	0.05	I, loop leg
7	20070327	143412	220	1.24	0.56	0.41	0.49	13.8	2.42	9.82	4.89	4.11	1.40	9.65	0.10	I, loop leg
8	20070328	031531	264	1.84	0.89	0.77	0.81	13.8	3.17	11.7	2.99	5.50	2.63	9.03	0.05	I, loop leg
9	20070328	183726	303	2.08	0.56	0.77	0.76	9.01	2.64	10.7	2.70	6.25	1.67	9.52	0.07	I, loop leg
10	20070216	163920	345	1.93	0.70	0.46	0.71	5.35	1.29	4.13	1.46	4.15	1.43	9.67	0.07	II, QS BP
11	20070221	194813	394	1.22	0.54	0.34	0.56	10.7	1.34	3.47	0.43	4.73	1.57	8.83	0.05	II, loop top
12	20070223	125943	384	1.09	0.46	0.22	0.45	6.37	1.46	4.91	2.19	2.09	0.95	9.27	0.07	II, loop top
13	20070223	185342	380	1.06	0.56	0.35	0.55	6.14	0.87	3.47	0.61	2.38	1.15	9.25	0.08	II, loop top
14	20070224	005742	381	1.27	0.54	0.34	0.57	5.84	1.68	3.18	0.67	2.48	1.08	9.31	0.09	II, loop top
15	20070224	130643	370	0.88	0.63	0.25	0.31	4.50	1.03	3.47	0.30	1.67	1.76	9.32	0.09	II, loop top
16	20070225	112113	185	0.91	0.66	0.19	0.46	[illegible]	[illegible]	4.91	1.29	1.95	1.58	9.10	0.05	II, unclear
17	20070326	150012	29	0.79	0.68	0.27	0.38	8.26	2.92	5.35	0.93	2.21	2.13	9.00	0.04	II, loop top
18	20070327	160926	247	0.80	0.74	0.28	0.38	6.94	2.05	4.91	1.12	2.04	1.70	9.16	0.03	II, loop top
19	20070328	031531	12	0.84	0.72	0.27	0.46	8.26	3.44	7.57	2.59	2.03	1.76	8.94	0.04	II, loop top
20	20070328	183726	40	0.64	0.67	0.26	0.33	12.7	1.01	4.91	0.67	1.78	1.77	9.14	0.03	II, loop top
21	20070419	191102	189	3.17	0.97	0.44	0.65	6.94	1.02	5.35	1.29	8.39	2.73	9.08	0.03	II, QS BP

Longitudinal

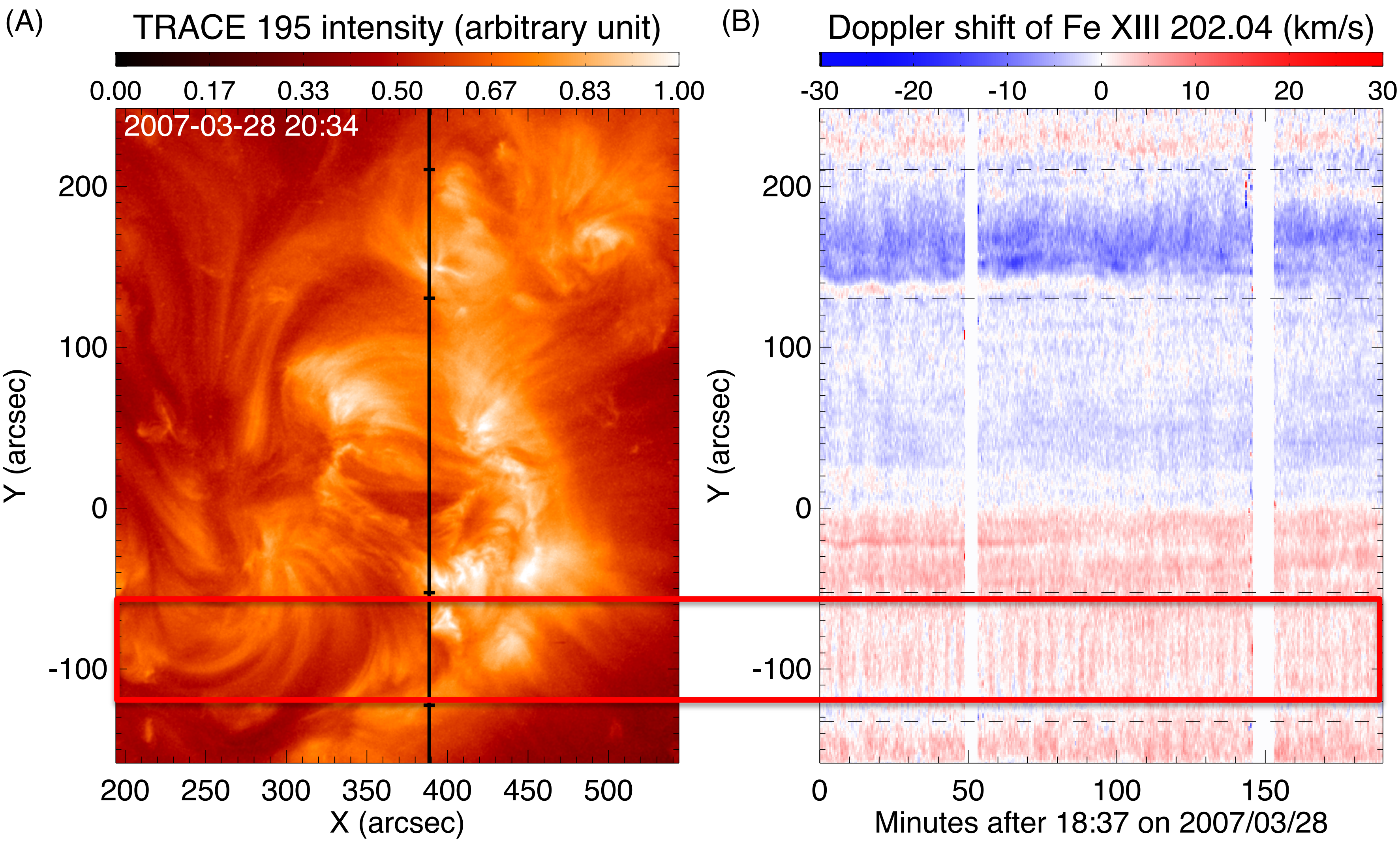
Transverse

Notes. The following information is listed for each event: observation date (yyyymmdd), starting time (hhmmss), lowest y-pixel of the selected 11-pixel region on the slit (*Y*), root-mean-square values of the detrended intensity (Ri, %), Doppler shift (Rv, km s^{-1}), line width (Rw, km s^{-1}) and RB asymmetry (Ra, %), intensity oscillation period and uncertainty (Pi and Piun, minutes), Doppler shift oscillation period and uncertainty (Pv and Pvun, minutes), amplitudes of intensity (Ai, %) and Doppler shift (Av, km s^{-1}) oscillations, electron density, and uncertainty (N and Nerr, log cm^{-3}), and oscillation type and location.

- Examined all EIS sit-n-stare observations in ARs during Feb to April 2007
- Decayless/persistent Doppler shift oscillations are very common

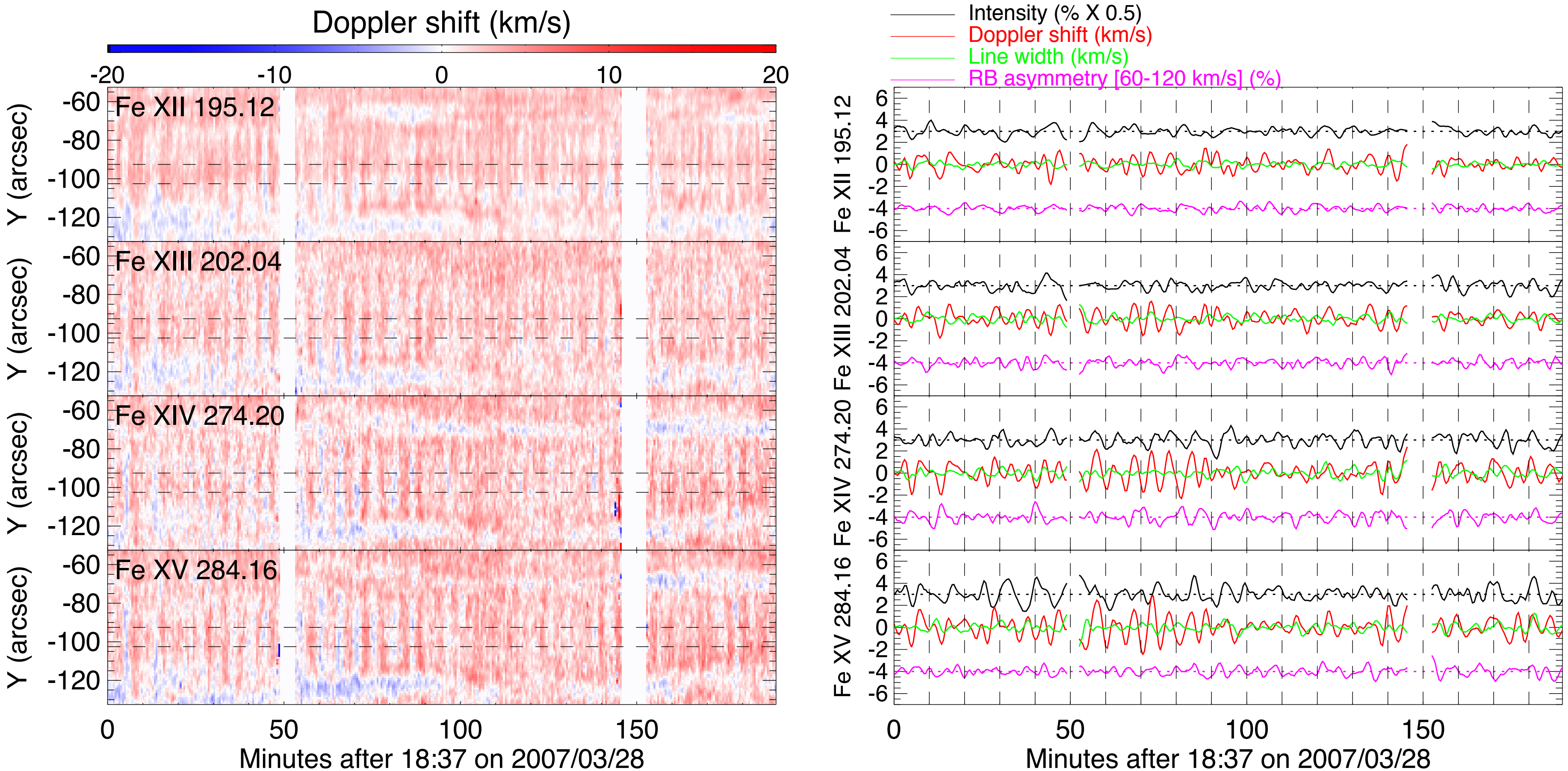
Tian et al. 2012, ApJ, 759, 144

Decayless transverse oscillations in coronal loops



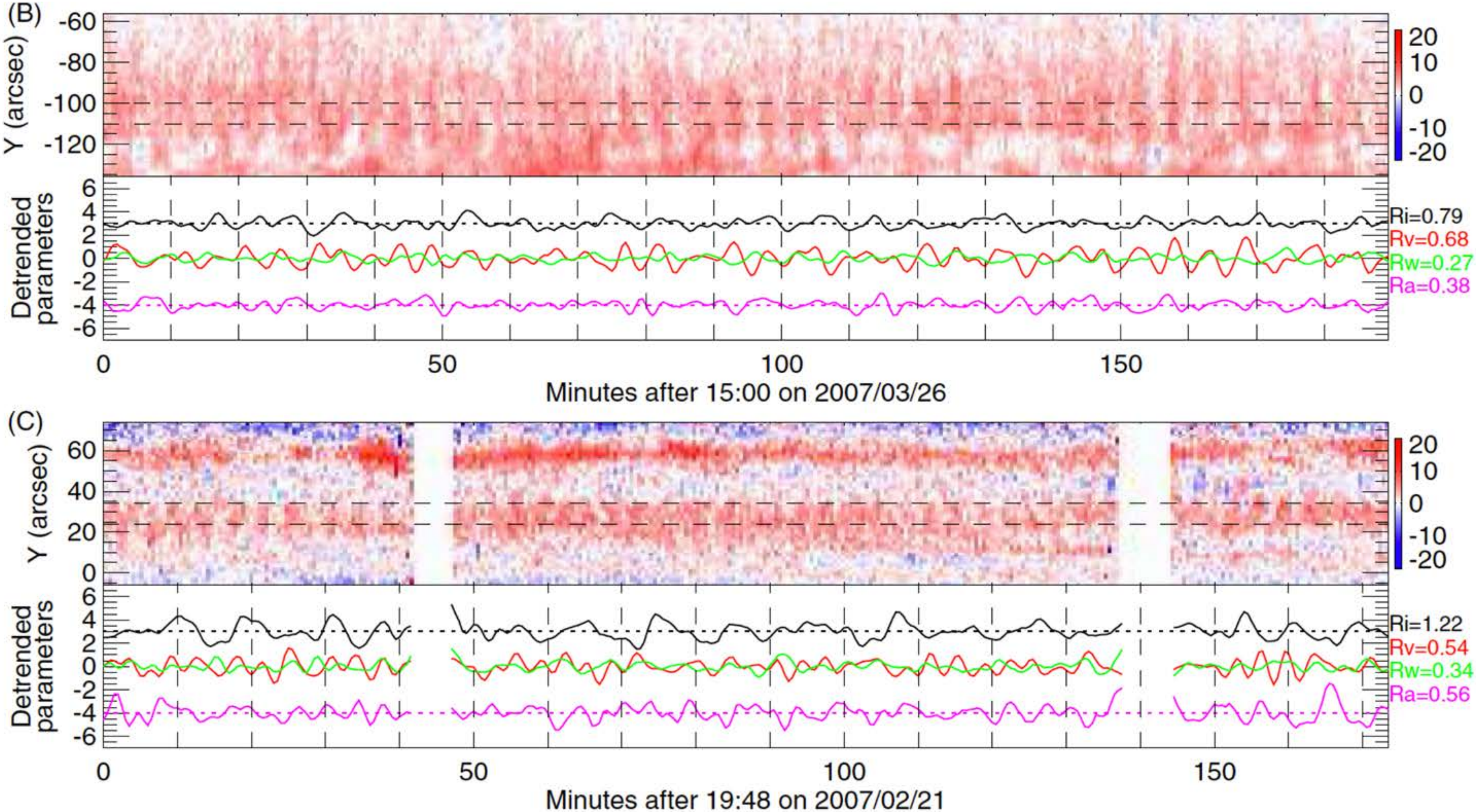
Usually found at top/higher part of the loops

Oscillations in all line parameters



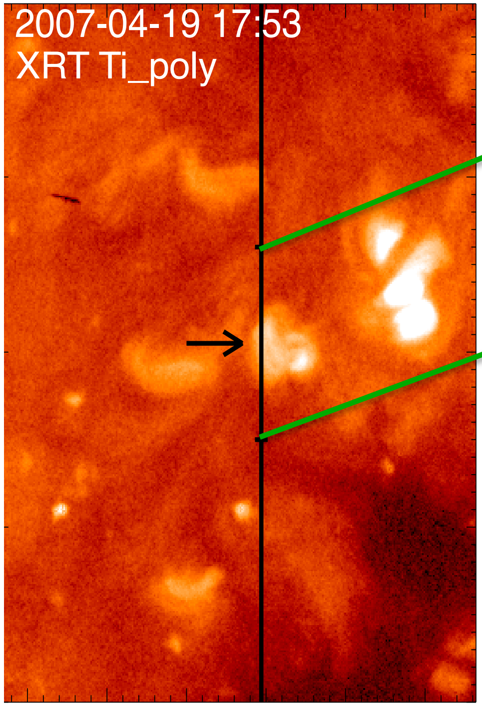
- Most prominent in Doppler shift of lines with T_f=1-2 MK, period 3-6 min
- Doppler shift amplitude ~2 km/s; Intensity variation ~2%
- Clearly decayless Alfvénic/kink oscillations

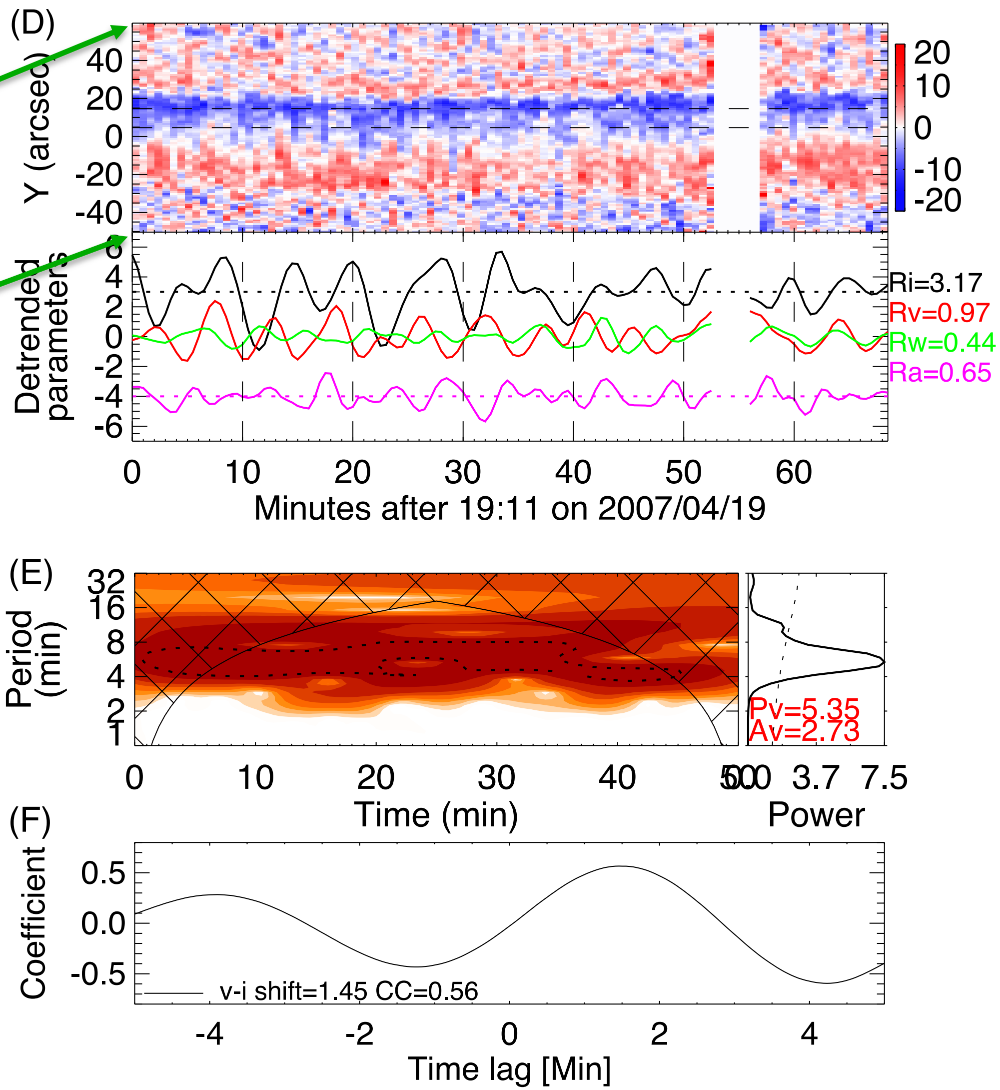
Other examples



These decayless transverse oscillations are commonly observed when the slit is aligned with the upper part of loops.

π/2 phase shift between intensity and Doppler shift

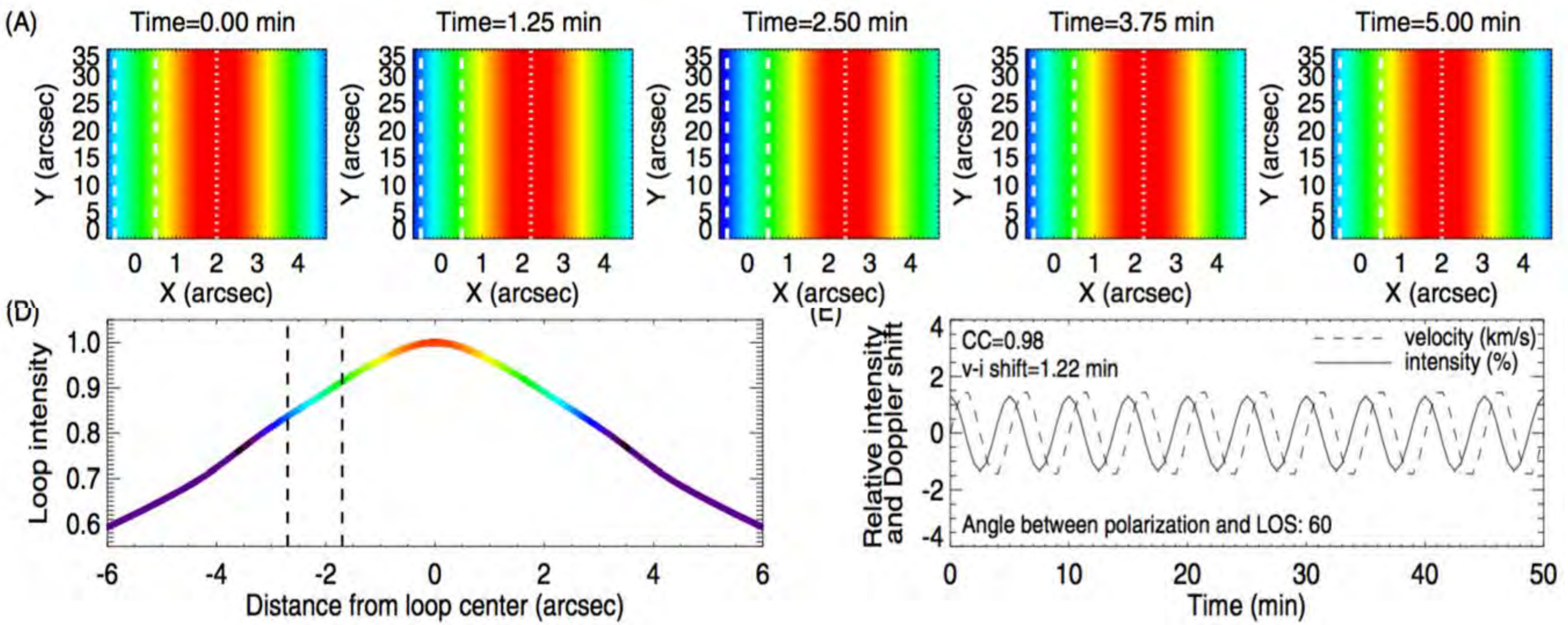




π/2 phase shift between Intensity and Doppler shift when slit is aligned with loop top

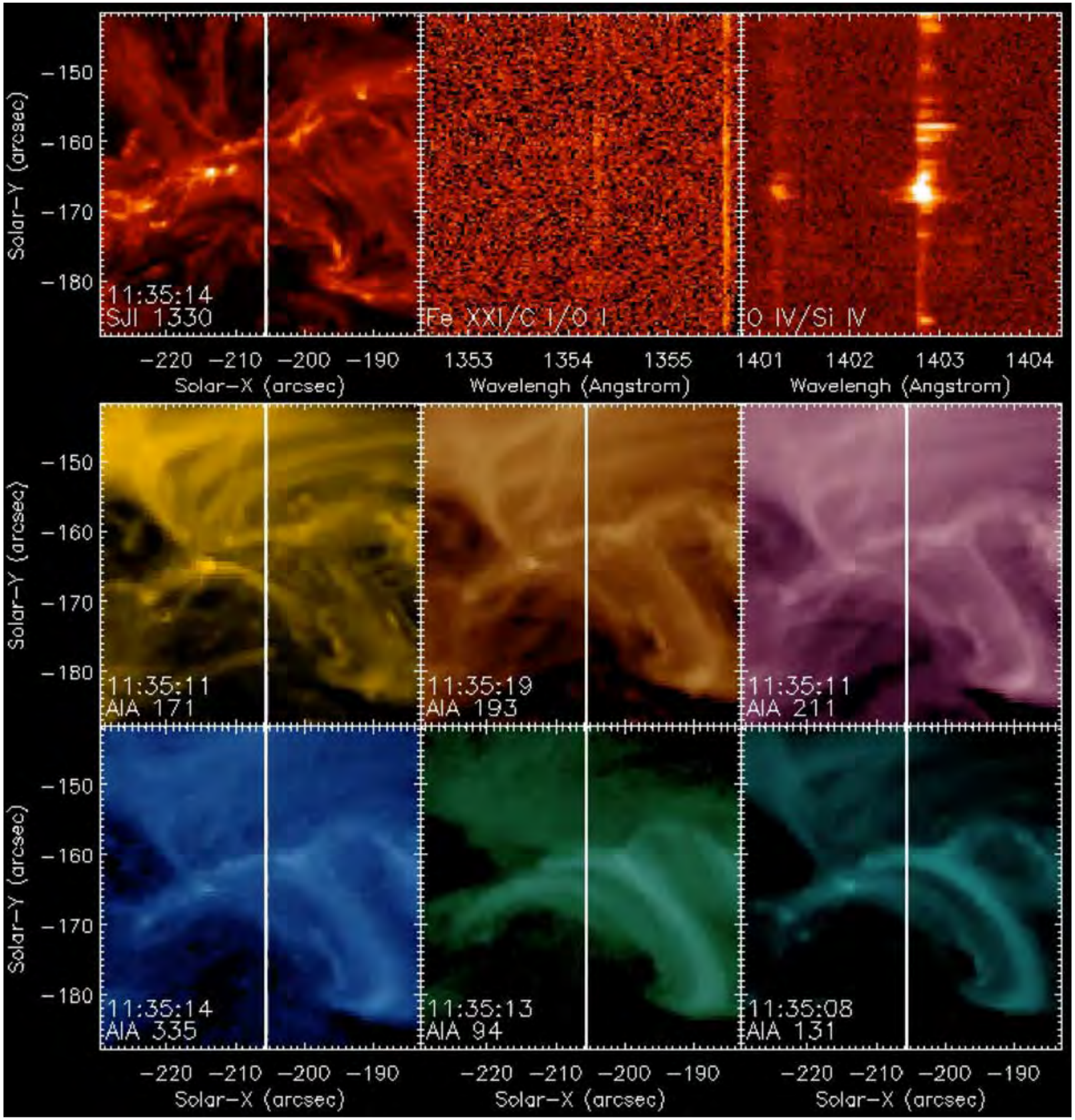
A new interpretation for the π/2 phase shift

Slit location: between two dashed lines; Loop center: dotted line



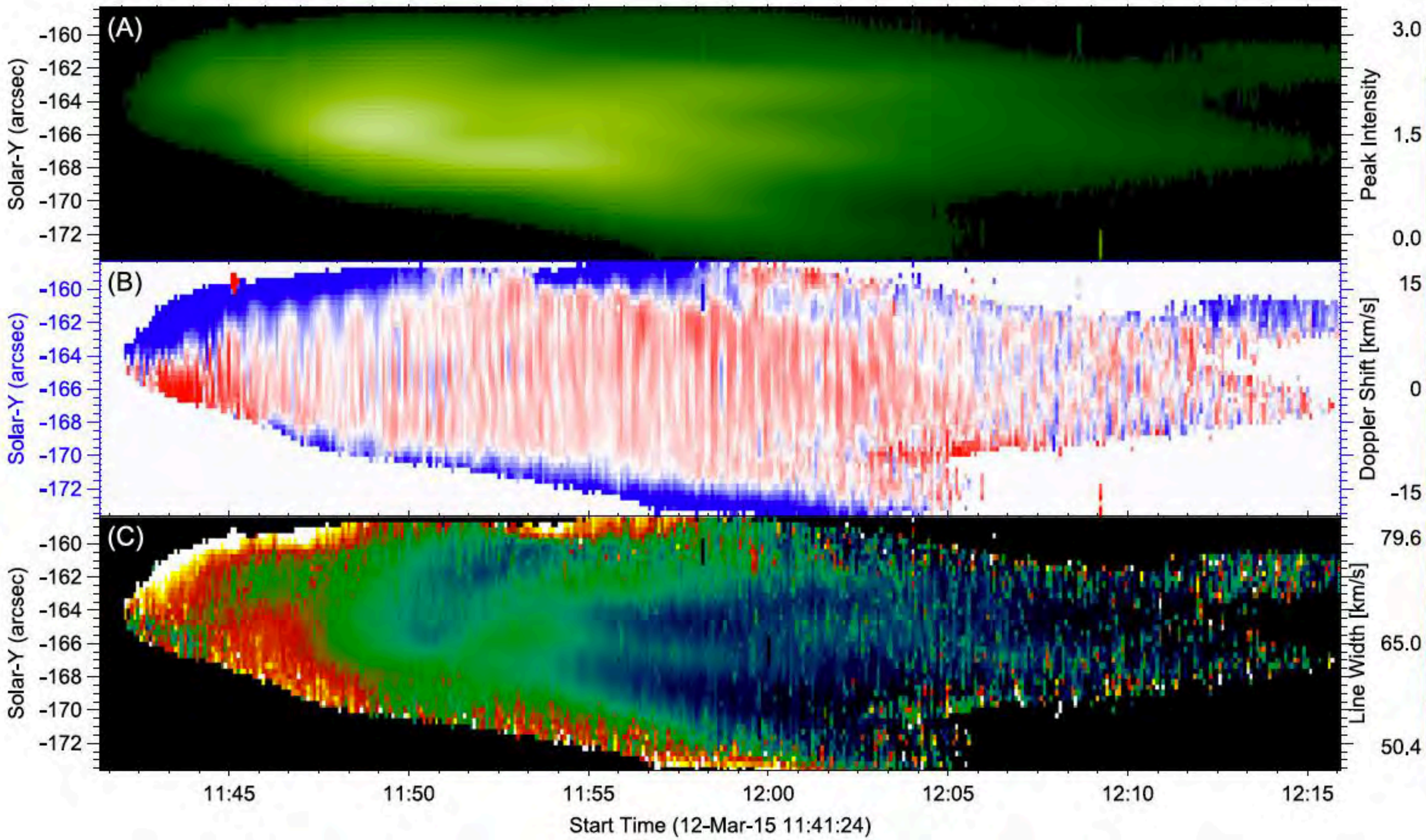
- Intensity oscillations could also occur in observations of Alfvénic/kink waves, since periodic loop displacement could lead to the scenario that different parts (with different intensity) of a loop are sampled periodically. In this case, the intensity change is not a reflection of density change.
- The phase shift could be produced by loops moving into and out of a spatial pixel as a result of transverse oscillations.

An M1.6 flare on 2015 March 12



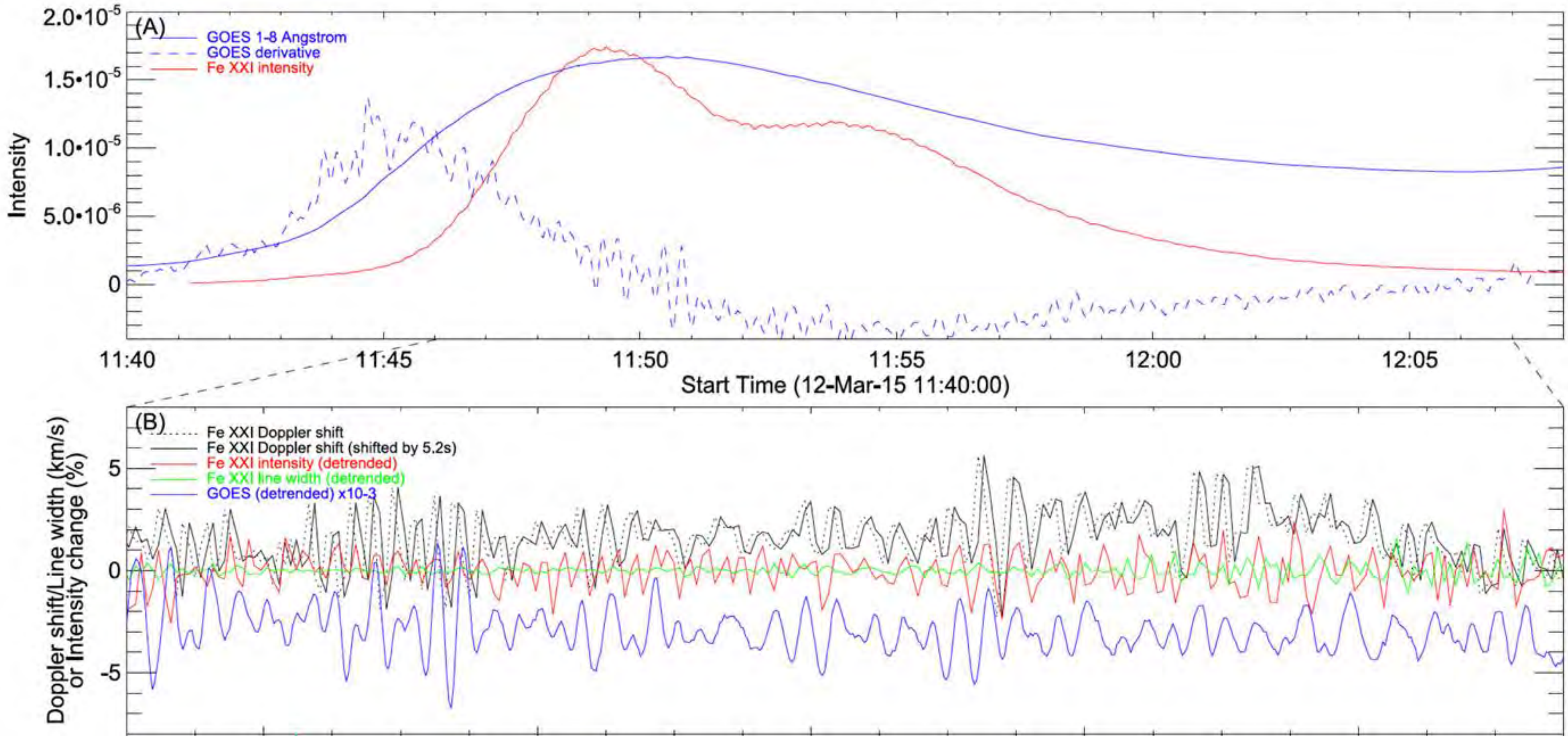
Tian et al. 2016, ApJL, 823, L16

Temporal evolution of Fe XXI line parameters



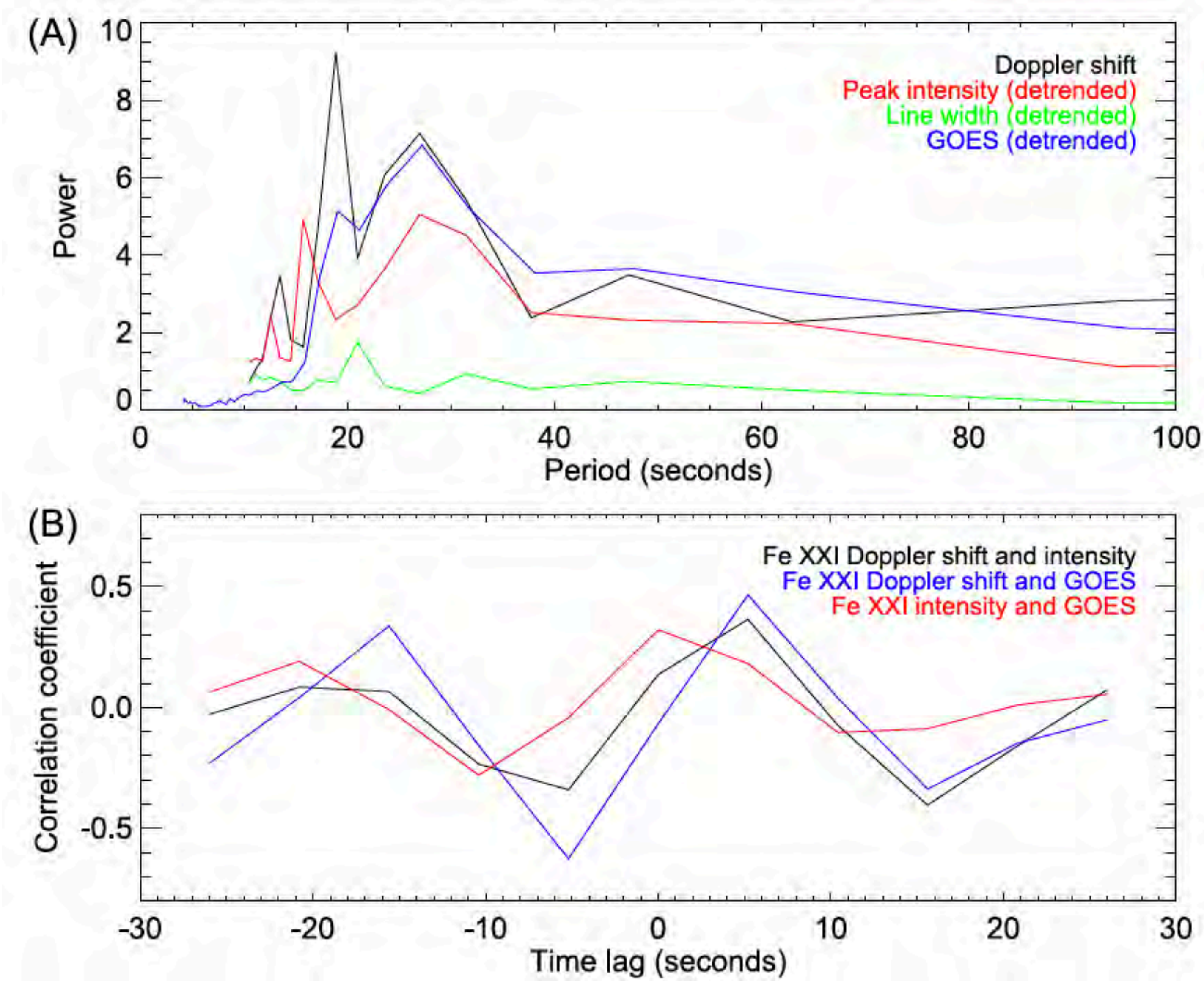
- Different loops oscillate with the same period (~25 s) and almost in phase: these loops oscillate as a whole and the oscillations are most likely standing waves.

Temporal evolution of Fe XXI line parameters



- In-phase oscillations of the spatially resolved Fe XXI intensity and the GOES flux integrated over the whole Sun
- A phase shift of ~ π/2 (1/4 period) between the Doppler shift oscillation and the intensity/GOES oscillations

π/2 phase shift between intensity and Doppler shift



Mode identification – global fast sausage mode

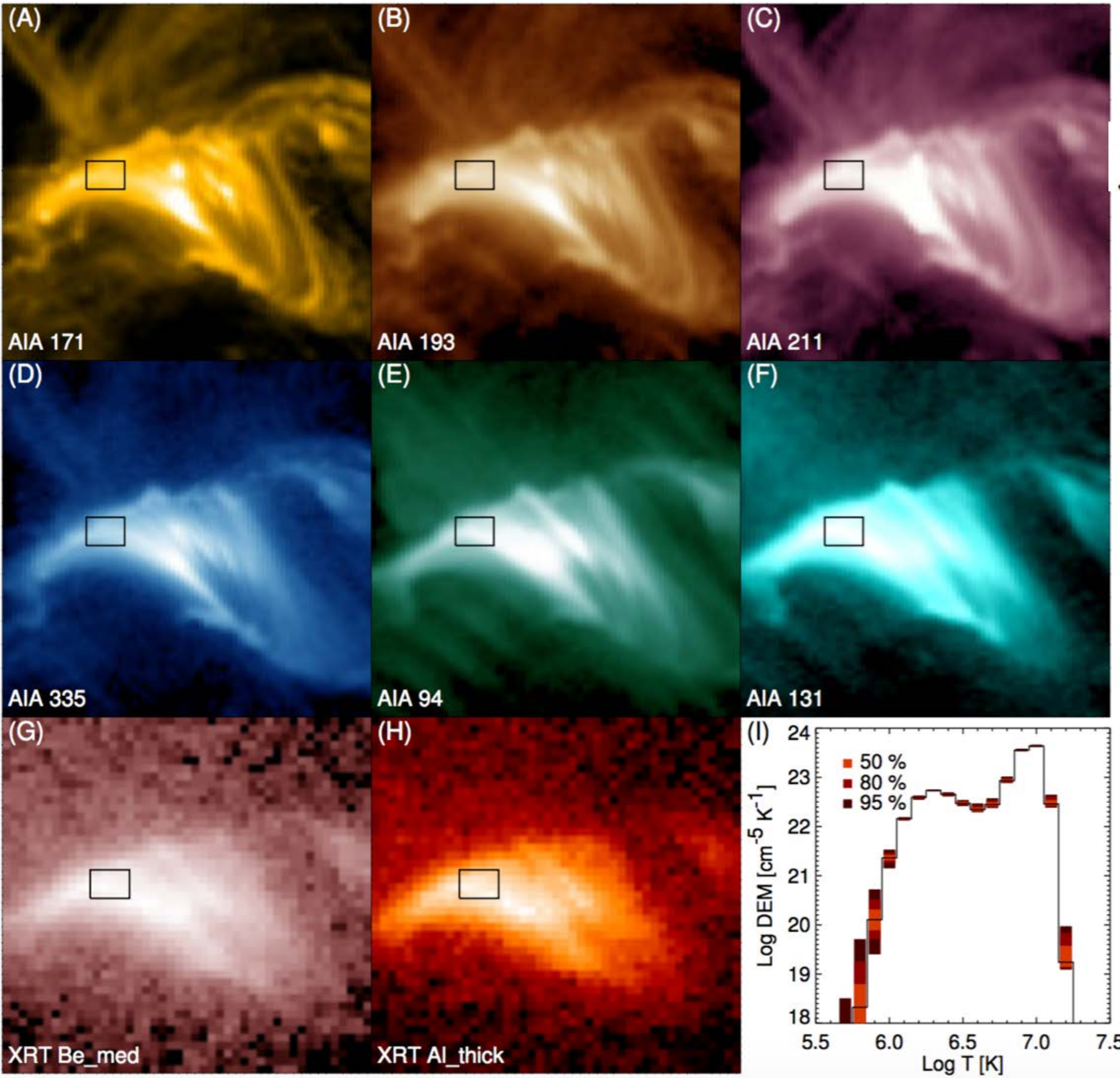
- Not slow modes: Phase speed ($C_p = 2L/P$) is ~2420 km/s, much higher than the sound speed ~525 km/s at 10 MK
- Likely not kink mode
  - Kink waves may cause azimuthal flows & geometry change, leading to intensity variation (Yuan & Van Doorsselaere 2016, Antolin & Van Doorsselaere 2013, Verwichte et al. 2009). But could not explain the same period of intensity/Doppler shift or their π/2 phase shift
  - Kink wave can lead to π/2 phase shift, but slit needs to be parallel to loops (Tian et al. 2012)
- Mostly likely global fast sausage mode
  - Phase speed smaller than and close to the external Alfven speed C_{Ae} (Nakariakov et al. 2003), which could be much larger than the Alfven speed in the dense flare loops
  - In the case of a non-90^o angle between LOS and loop, forward modeling of sausage mode (Antolin & Van Doorsselaere 2013) predicts a π/2 phase shift between intensity and Doppler shift, reduced intensity and line width fluctuations
  - Observational signatures reproduced by a forward modeling of fundamental fast sausage modes with non-equilibrium ionization (Shi et al. 2019)

Density contrast

- Global sausage mode can only exist in dense and thick loops (Nakariakov et al. 2003; Aschwanden et al. 2004).
- Since all loops oscillate as a whole, they should be regarded as one loop here (loop cross section diameter 10”). Effects due to fine structuring can be ignored when performing coronal seismology for fast sausage oscillations (Chen et al. 2015).

$$\frac{\rho_0}{\rho_e} > \left(\frac{L}{0.65a}\right)^2$$

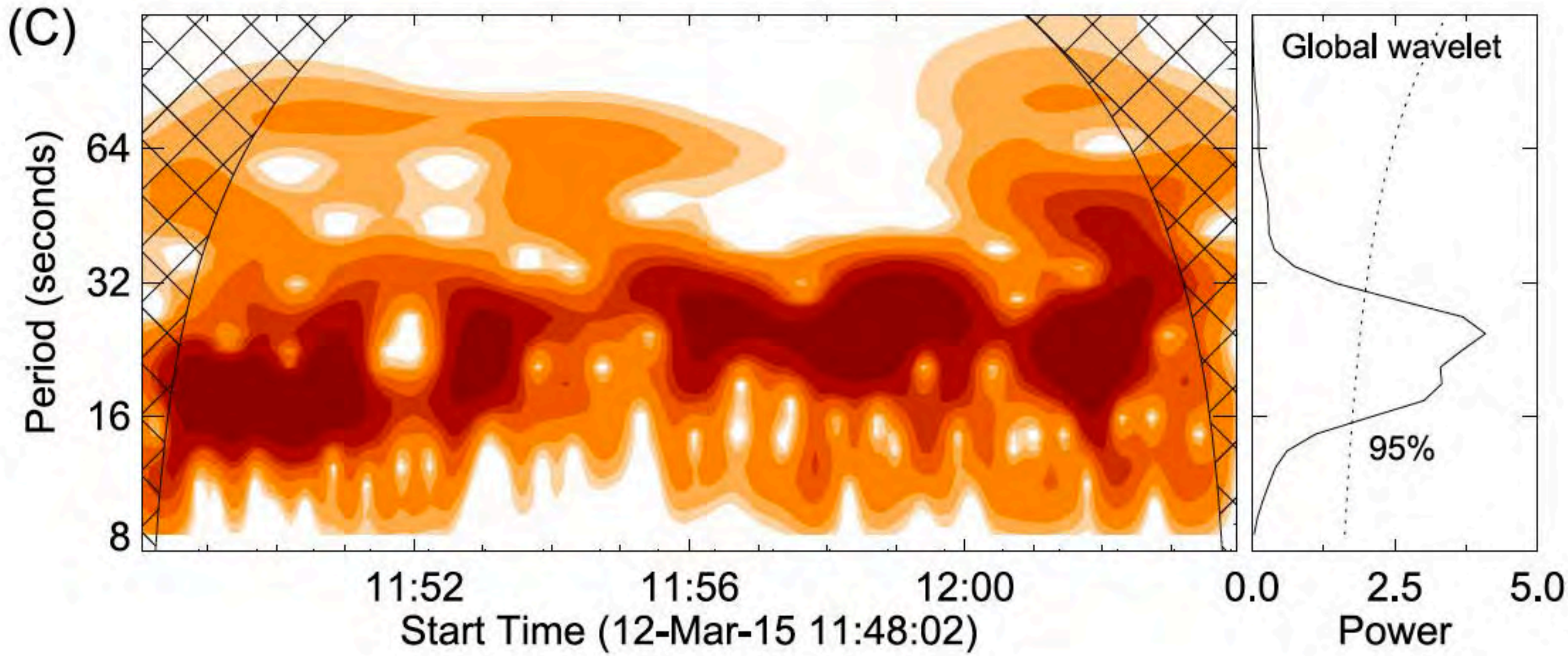
- So the density contrast has to be larger than 42.



$$\int DEM(T)dT = fN_e^2 a$$

From DEM analysis, loop density > 5.4×10^{10} cm^{-3}. The density contrast will be >54 if we take the typical external coronal density 10^9 cm^{-3}, satisfying the necessary condition for the existence of global sausage mode.

Evolving period



- Two dominant periods at 19 s and 27 s
- The 19 s period: likely not the second harmonic, but caused by change of the loop internal condition (*N, B, L*)

Conclusion

- Persistent or decayless (without obvious damping) oscillations are identified from spectroscopic observations of coronal loops and flare loops. These two types of decayless oscillations are most likely Alfvénic/kink waves and fast sausage waves, respectively.

- A $\pi/2$ phase shift between intensity and Doppler shift is not necessarily a signature of slow standing waves, could also be produced in the case of Alfvénic/kink or sausage oscillations!

- Two dominant periods in one time series are not necessarily different harmonics, could be caused by the change in the physical conditions of loops.