MHD Coronal Seismology with ALMA

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What would we like to see and why?
Lightcurves (hard and soft X-ray, microwave, white light) of flaring energy releases often have quasi-periodic pulsations (QPP).
Typical examples:

“The Seven Sisters Flare” – Kane et al. (1983), with ISEE-3 and Nobeyama Radiopolarimeter, the period was about 8 s.

(+ very faint pulsations in < 17 GHz)
Often QPP are seen in both microwave (GS) and hard X-ray: e.g. Asai et al. (2001)
QPP in sub-THz band (see the talk of P. Kaufmann for details)
Intrinsic modes (determined with the Huang-Hilbert Transform) are essentially anharmonic:

**Figure 2.** Oscillatory components of the flare on 29 May 2003 in the microwave flux at 9.4 GHz, measured with the NoRP (upper panel) and in the hard x-ray flux measured with ACS (lower panel). The components were obtained by summing up three intrinsic modes of the signals, determined with the empirical mode decomposition technique.
Kupriyanova et al., *Solar Phys.* 267, 329, 2010 used NoRH and NoRP:

“In ten out of twelve considered events, at least one or more significant spectral components with periods from 5 – 60 s have been found.”
Typical periods: a few s – several mins

Typical scales: 1 Mm – 100 Mm

If connected with MHD waves or other MHD processes:
  typical speeds 0.1-5 Mm/s
  (consistent with estimations)

Possible mechanisms for QPPs:
- “Magnetic dripping” – spontaneous periodic reconnection;
- Direct modulation of the emitting plasma and magnetic field, and of the efficiency of particle acceleration by MHD waves;
- Indirect induction by MHD waves: periodic triggering of reconnection and/or particle acceleration.
Wave and oscillatory processes in the solar corona:

- Observational evidence of coronal oscillations (or quasi-periodic pulsations) is abundant (major contribution by SOHO, TRACE, NoRH, now Hinode and SDO).

- Possible relevance to coronal heating and solar wind acceleration problems.

- Possible role in the physics of solar flares.

- **Plasma diagnostics**: MHD seismology (c.f. magneto(spheric)seismology and MHD spectroscopy of tokamaks).
MHD Waves in the Corona:

Alfvén waves:
• essentially incompressible,
• transverse,
• individual for different Alfvénic ($C_A=\text{const}$) surfaces (phase-mixed)

Fast magnetoacoustic waves:
• compressive (in some limits – weakly compressive, “Alfvénic”)
• oblique (longitudinal for perpendicular propagation).
• collective

Slow magnetoacoustic:
• compressive,
• oblique (longitudinal for parallel propagation).
• collective
Interaction of MHD waves with **coronal plasma structures**
(V. Zaitsev, A. Stepanov, B. Roberts and colleagues, 1975-)

Dispersions relation of MHD modes of a magnetic flux tube:

\[ \rho_e (\omega^2 - k_z C_{Ae}^2) m_0 \frac{I_m'(m_0 a)}{I_m(m_0 a)} - \rho_0 (\omega^2 - k_z C_{A0}^2) m_e \frac{K_m'(m_e a)}{K_m(m_e a)} = 0 \]
1. Kink oscillations of coronal loops (Aschwanden et al. 1999, Nakariakov et al. 1999, and many authors later)

2. Propagating longitudinal waves in polar plumes and near loop footpoints (Berghmans & Clette, 1999; Nakariakov et al. 2000, De Moortel et al. 2000-2004, and many authors later)

3. Standing longitudinal waves in coronal loops (Kliem et al. 2002; Wang & Ofman 2002; and many authors later)


Main achievements of MHD seismology of the corona since 1999:

- Measurement of the average magnetic field in coronal loops (became one of the aims of SDO/AIA),
- Estimation of the density scale height in the corona,
- Evidence of sub-resolution field-aligned structuring of active regions in density,
- Demonstration of the presence of Alfvénic upflow jets in supra-arcades of flaring active regions.
Also, potentially MHD seismology could:

- Measure the **magnetic twist** in coronal loops,
- Estimate the coronal **heating function**,
- Reveal the **transport coefficients**,
- ...

The further progress requires better *time and spatial resolution simultaneously*: both projected wavelength and the wave period should be resolved.
Example: kink oscillations of coronal loops and prominence fibrils:
Simulated **time-distance** plot of kink oscillations:

0.6” AIA:  

0.2” ALMA:
Decay time vs Period: \[ \tau = P^{0.98 \pm 0.09} \]

Presently, consistent with damping via resonant absorption \( \rightarrow \) information about \textit{transverse structuring}
Better spatial resolution: more events detected. The number of events $N$ is likely to depend upon the displacement amplitude $A$ as

$$N \propto \frac{1}{A^\alpha}$$

(less powerful oscillation are more probable, and also the LOS effect). The index alpha is likely to be $> 2$ or $3$.

Thus, 0.2-0.3” resolution will give us **15-20 times more kink oscillation events: crucial for statistical studies.**
Example: Sausage mode:

m=0 mode

Leaky regime:

Trapped regime:
Sausage mode is essentially **compressible** and can **modulate EUV and X-ray** directly,
and **radio emission**, directly, through rho and $|B|$

or through the modulation of the mirror ratio of non-thermal electrons

(the Zaitsev-Stepanov mechanism)
Different radial steepness indices:

Typical periods 0.5-50 s

The independence of the period of the wavelength: great for seismology!
Observability: Effect of LOS integration:

For GS emission in the local approximation see Mossessian & Fleishman 2012.

C.f. Cooper et al. 2003a,b for kink waves.

(for GS emission in the local approximation see Mossessian & Fleishman 2012)
Consider optically thin thermal emission:

\[ I(t) = \int_{\text{(LOS)}} \varphi^2(r, t) \, dx. \]

Again, the pixel size does matter!
Why ALMA?

- **Spatially resolving** observations of the **short-time** variability of non-thermal emission from flaring active regions in **different** mm and sub-mm bands. (Also, the waves are likely to be excited in the vicinity of energy releases!)
Specific scientific objects:

- Flare-generated fast (kink and sausage) propagating wave trains in the vicinity of the flare epicentre.

- Kink and sausage oscillations of loops in the flaring AR – need for resolving the specific time dependence of the decay, higher spatial harmonics, oscillations in short loops.

- The effect of Alfvénic vortex shedding, and its possible relevance to the selectivity of excitation.

- Evidence of the “periodic magnetic dripping”?

- Evidence of triggering of flares by waves?

- Ballooning modes?
Advantages of QPP studies for ALMA operations planning:

- Only relative variations of the emission intensity are needed (low sensitivity to calibration)

- Even the resolution a bit less than 1” would give breakthrough results.

- Targeting can be realistic: e.g. large active regions on-disk and off-limb. The same with prominences.

- Usually no need for a dedicated observational programme: can use data of other programmes (c.f. the great but unexpected success of TRACE)
How can it be done?

Let us discuss it.

But, an arrangement of this kind:

- FOV of 20"x20" with spatial resolution 0.3", targeted on an “flare-active” AR in a sit-and-stare mode with time cadence 0.1 s in e.g. 160 GHz

seems to be realistic and is likely to bring us paradigm-changing breakthroughs.

We don’t have to wait for a large X-class flare: even with TRACE we saw kink oscillations in C-class flares.
The aim of this project is to establish close research interaction and collaboration between the key EU and non-EU research groups involved in research of the Sun in the radio band; qualitatively advance our knowledge of the physical processes operating in the solar atmosphere, the mechanisms responsible for its evolution and dynamics and its effect on the Earth; provide younger researchers with extensive training in research techniques and with universal transferrable skills. The participating teams are either actively involved or host world-leading upcoming.

Warwick, Glasgow, Ondrejov, Lublin and NOAC, Irkutsk and Pulkovo

One of the aims is forward modelling of wave and oscillatory processes in the solar atmosphere for ALMA, and the data analysis when available.
Research Assistant Or Research Fellow (2 Posts)

Physics

£23,811 - £26,779 pa or £27,578 - £35,938 pa

Fixed Term Contract from 1 April 2013 until 31 March 2015

The Centre for Fusion, Space & Astrophysics at the University of Warwick is seeking two ambitious post-doctoral researchers to work within the project "Magnetohydrodynamic wave diagnostics of the solar atmosphere in the era of transformative high-resolution observations". The positions are funded by an ERC Advanced Grant held by Valery Nakariakov, and this team will include at least two PhD students as well. The project comprises of the analysis of data obtained with space-borne telescopes including SDO, Hinode, STEREO and RHESSI, and future missions, and ground-based observational facilities, and analytical and numerical modelling of these phenomena, including high-performance MHD and plasma simulations, and plasma diagnostics.