MUSE EUV spectroscopy of a coronal loop system undergoing MHD-avalanche
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Gabriele Cozzo[1]
J. Reid[2], P. Pagano[1,3], F. Reale[1,3], A. W. Hood[2],
C. Argiroffi[1,3], A. Petralia[3], E.Alaimo[1,3], F. D'anca[3], L. Sciortino[1,3],
M. Todaro[3], U. Lo Cicero[3], M. Barbera[1,3], P. Testa[4]

1. Dipartimento di Fisica & Chimica, Università di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy
2. School of Mathematics and Statistics, University of St Andrews, St Andrews, Fife, KY16 9SS, UK
3. INAF-Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy
4. Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

1 State of the Art

The solar corona consists of plasma confined by, and interacting with, the coronal magnetic field. It fills up dense, bright, filamentary structures, supported by an arc-like magnetic field, known as coronal loops. They display starkly high temperatures (above one million kelvin) whose explanation still persists as a long standing problem.

In the contemporary understanding, there is widespread acknowledgment of the magnetic field's predominant role as the primary source of heating energy. In particular, to address the coronal heating problem, two mechanisms have been envisaged: one involves the dissipation of stored magnetic stresses, referred to as DC heating, and the other involves the damping of MHD waves, known as AC heating.

DC heating involves magnetic energy storage and impulsive, widespread release. In fact, as the magnetic field builds up in the solar corona, it continuously departs from its potential state and provides free-energy storage to be converted into internal plasma energy. In particular, turbulent photospheric motions induce coronal magnetic field lines to twist and tangle with each other, ultimately providing inevitable growth of magnetic stresses. As a consequence of the ongoing stirring of plasma in the photosphere caused by magnetoconvection, the magnetic field lines forming coronal loops are induced to exhibit intricate braiding patterns at extremely fine resolutions, smaller than an arcsecond. Parker envisaged that this ongoing process would ultimately give rise to widespread formation of tangential discontinuities in magnetic field and minuscule current sheets within the solar corona. These discontinuities would serve as sites for magnetic reconnection events, leading to the release of small amounts of energy on a nanoflare scale.

Although photospheric plasma induces slow and local dragging of magnetic field lines at loop footpoints, according to Parker's theory, magnetic energy release in the large scale coronal environment is expected to occur through impulsive and widespread heating events. One potential heating mechanism that can effectively blend a slow, enduring influence at the boundary with rapid, unpredictable surges of energy release is the avalanche model. In this model, a localized MHD instability within a single strand of a coronal loop triggers a global MHD instability as neighboring loop filaments become affected by the propagating disturbance. This mechanism offers a promising explanation for the complex interplay between slow and fast processes in coronal energy release. In particular, as turbulent motion induce loop's magnetic field lines twisting, such flux tubes can become susceptible to kink instability, resulting in the release of magnetic energy through sudden, widespread heating events. The initial helical current sheet progressively fragments in a turbulent way into smaller scale sheets. The turbulent dissipation of the magnetic structure into small-scale current sheets converts into a sequence of a-periodic, impulsive, heating events, similarly to nanoflare storms.

This work addresses the diagnostics of a MHD avalanche process in the solar corona with the future MUSE instrument, a proposed NASA mission oriented to study the solar EUV corona at high spatial ($\Delta\theta \sim 0.167\,\mathrm{arcsec}$) and temporal ($\Delta t \sim 10\,\mathrm{s}$) resolutions.

The full 3D MHD model developed by G. Cozzo et al 2023 provides a self consistent description of a large scale energy release in a stratified atmosphere. It accounts for a multi-threaded coronal loop made up by two interacting magnetic strands, subjected to twisting at the photospheric boundaries. The global, turbulent decay of the magnetic structure is triggered by the disruption of a single coronal loop strand, made unstable under kink instability by twisting. Current sheets formation, fragmentation and dissipation provides impulsive heating and rapid temperature increase. Efficient field aligned thermal conduction induces chromospheric ablation and in turns a over-density state in the corona. Optically thin radiative losses are assumed in the corona.

The model allows both space and time resolved diagnostics. In particular we synthesized MUSE spectrometer response at Fe IX, Fe XV and XIX emission lines, providing cold ($\sim 1\,\mathrm{MK}$), warm ($\sim 2\,\mathrm{MK}$) and hot ($\sim 10\,\mathrm{MK}$) plasma diagnostics, respectively.

Irregular line profiles are expected due to the turbulent, impulsive behaviour of the instability. This is suggested comparing averaged plasma velocity ($\leq 10^7\,\mathrm{cms}^{-1}$) with averaged temperature ($\leq 10^7\mathrm{K}$) and confirmed by slit-averaged line profiles. We thus synthesized emission line intensity, weighted averaged Doppler shifts, and non-thermal line broadening for each emission line.

In all cases we conclusively show how the three lines provides plasma information at different places, dynamical stages and physical conditions. In particular, they efficiently disentangle the instability evolution into: (**Fe IX**) foot point response and plasma ablation at transition region; (**Fe XV**) over-dense and warm plasma rising at intermediate heights; and (**Fe XIX**) hot flaring plasma inside current sheets.

A grate amount of information can be retrieved from lines emission. In particular, Fe XIX revealed as fair proxy of strong and dynamic current buildups such as current sheets are supposed to be. They form and rapidly dissipate during the earliest, most violent phase of the instability. During the same dynamic range i.e. at the time of the treads disruption, Fe IX footpoints response provides complementary information about the status of the magnetic structure, suggesting a potential diagnostics role in extrapolating information about the linear phase of the instability, as it might outclass the observational restriction imposed by the small counts-rate obtained with Fe XIX line. Outside the early stages of the instability, Fe XV emission returns information about the evaporation process triggered by the avalanche. Its is the only case in which almost the whole coronal loop structure becomes visible to the instrument.

Doppler shifts and non thermal line broadening can provide additional information about the plasma dynamics, confirming the strongly turbulent behaviour of the avalanche process, otherwise difficult to grasp only from emission maps analysis. Doppler shift maps also bring in complementary information on the strength of the chromospheric evaporation nearby footpoints.

2 Desiderata

To make meaningful predictions that can be compared with solar observations, two critical advancements are essential. First, the modeling approach must encompass all crucial physical components, including a comprehensive representation of the plasma atmosphere, to derive realistic observational outcomes. Second, observational techniques must achieve sufficient temporal and spatial resolution within the pertinent spectral bands. The synergistic comparison between coronal observations and synthetic plasma diagnostics from numerical simulations can therefore significantly improve, from one side, our interpretative power on real observational data and tune, on the other side, the solar corona modelling.

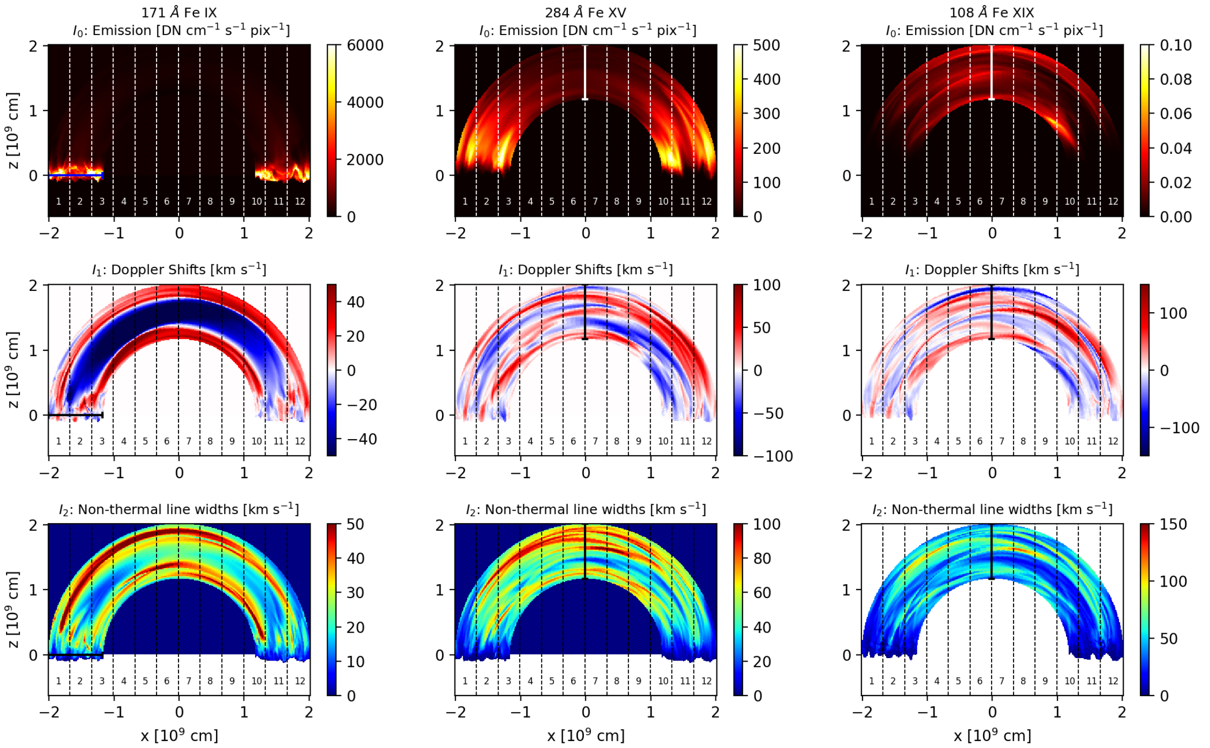

Figure 1: MUSE synthetic maps, from PLUTO 3D MHD model of a multi-threaded magnetic flux tube. Here we show the tube structure at time $\sim$ 175s after the onset of the instability and with the l.o.s. along the $\hat{z}$ direction. The top row shows the intensity of Fe IX, Fe XV, and Fe XIX emission lines. The middle row instead shows the related line shifts. The bottom row shows the non-thermal line broadenings. Dashed, vertical lines divide the domain into 12 parts, labeled by numbers. The horizontal extension is equal to the angular coverage of a single MUSE slit.