Thermal x-ray emission in kink-unstable coronal loops

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Abstract

Goals: Investigate the temporal evolution of the thermal x-ray emission on kink-unstable coronal loops.

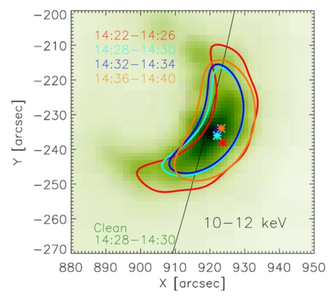
Results: The apparent twist (deduced from the emission morphology) is substantially smaller than the maximum twist in the simulated flux-ropes. The thermal emission spectrum undergoes three distinct phases, characterised respectively by moderate adiabatic heating, strong ohmic heating (and hardening of the spectrum) and conductive cooling. The plasma emission measure $EM(T)$ evolves from an initial Dirac-$\delta(T_0)$ distribution to a power-law $EM \propto T^{-4.2}$ (above $T = 2 \times 10^6$ K).

Context: Solar flares, reconnection, X-ray emission, interpretation of RHESSI and STIX X-ray data.

Methods: Numerical MHD simulations of eruptive coronal loops.

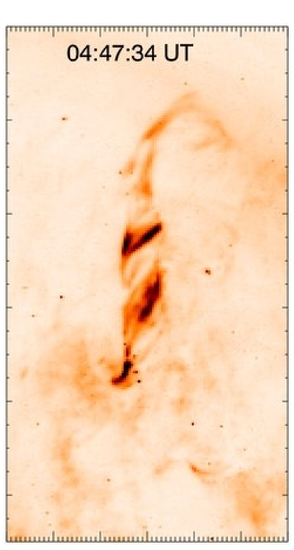
1. Flaring loops observations in X-rays

Solar Orbiter



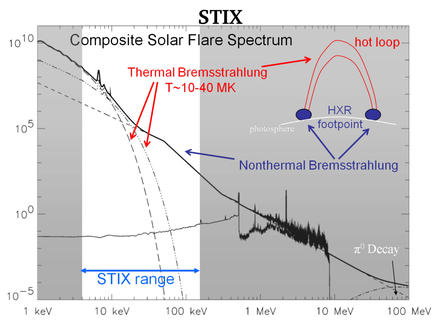
(RHESSI; Jeffrey & Kontar, 2013)

↑ Apparent **loop cross-section and length** ("corpulence") grow in time.



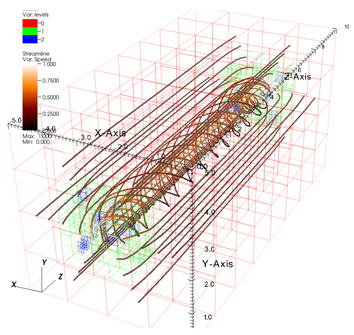
(TRACE 171; Srivastava et al., 2010)
↑ **Magnetic twist visible in EUV**
Enough twist for kink instability?
(This case:
$L = 80$ Mm, $r = 4$ Mm, $\phi = 12\pi$)

STIX



← **Soft (thermal) X-ray emission** within the loops;
Hard X-ray emission (usually) at the footpoints;
EUV ribbons

2. Methods



PLUTO MHD parallel code, good MPI scaling (Mignone et al., 2007, 2012).

Resistive MHD, finite-volume solvers, AMR,
Spitzer-Härm thermal conduction, radiative losses.

Running on BlueGene/Q (Turing, IDRIS) and BullX (Curie, TGCC).

→ Thermal X-ray emission

$\rho(\mathbf{r},t), T(\mathbf{r},t) \rightarrow$ Thermal emission and photon fluxes at all points and times
Spectra, light-curves, emission measures ($EM = n^2 V$)

→ Test-particle trajectories

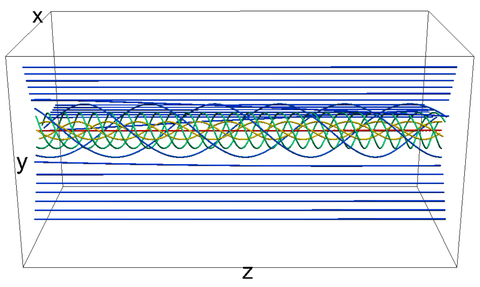
· direct integration of $d/dt(\gamma m \mathbf{v}) = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
· guiding-centre approximation equations
(Northrop, 1964).

Initial conditions

Force-free twisted flux-rope,
uniform background field.

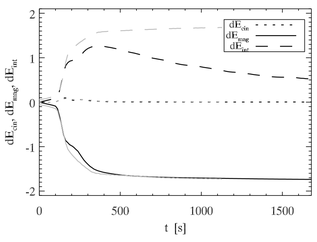
Parameters:
$L_0 = 50$ Mm, $T_{cor} = 1.2$ MK, $B_0 = 100$ G, $n_0 \approx 10^{10}$ cm^{-3}, $\tau_A \approx 25$ s

boundary conditions:
line-tied in z, periodic in the transverse directions, open to heat flux.
(*Similar models:* Botha et al., 2011; Gordovskyy & Browning, 2011; Hood et al., 2009)



3. Energy budget

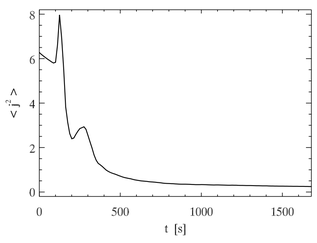
Energy budget



ΔE_{cin}, ΔE_{mag}, ΔE_{int}

ΔE_{cin} small
$\Delta E_{mag} \approx -\Delta E_{int}$ during the initial phases
ΔE_{int} decreases during the relaxation phase (conductive cooling)

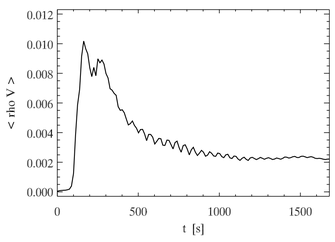
Grey lines: control case with no SH conduction



$\langle j^2 \rangle$

Strong peak at the saturation phase (strong ohmic heating)

Current vanishes as the magnetic field relaxes towards a potential-field state.



$\langle \rho v \rangle$

Strong peak, slow relaxation, residual small scale flows

Variations of the **total kinetic, magnetic and internal energies** (ΔE_{cin}, ΔE_{mag}, ΔE_{int}), **average current density squared** $\langle j^2 \rangle$, and **average linear momentum** $\langle \rho v \rangle$ (dimensionless units).

4. References

Botha, G. J. J., Arber, T. D., & Hood, A. W. 2011, Astronomy and Astrophysics, 525, 96

Gordovskyy, M. & Browning, P. K. 2011, Solar Physics

Gordovskyy, M., Browning, P. K., Kontar, E. P., & Bian, N. H. 2013, Solar Physics, 284, 489

Hood, A. W., Browning, P. K., & Linden, R. A. M. V. d. 2009, Astronomy and Astrophysics, 506, 13 pages

Jeffrey, N. L. S. & Kontar, E. P. 2013, The Astrophysical Journal, 766, 75

Mignone, A., Bodo, G., Massaglia, S., et al. 2007, The Astrophysical Journal Supplement Series, 170, 228

Mignone, A., Zanni, C., Tzeferacos, P., et al. 2012, The Astrophysical Journal Supplement Series, 198, 7

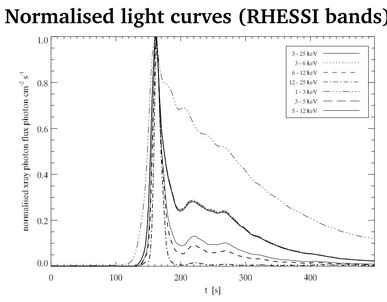
Northrop, T. G. 1964, American Journal of Physics, 32, 807

Srivastava, A. K., Zaqarashvili, T. V., Kumar, P., & Khodachenko, M. L. 2010, The Astrophysical Journal, 715, 292

5. Global emission

Light-curves

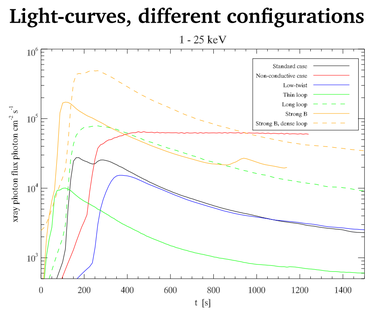
Normalised light curves (RHESSI bands)



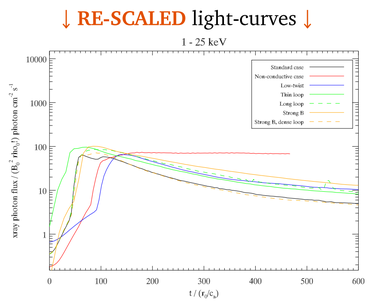
Low energy bands ⇒ **slow** decay;
High energy bands ⇒ **fast** decay

Scaling laws

Light-curves, different configurations



↓ **RE-SCALED** light-curves ↓



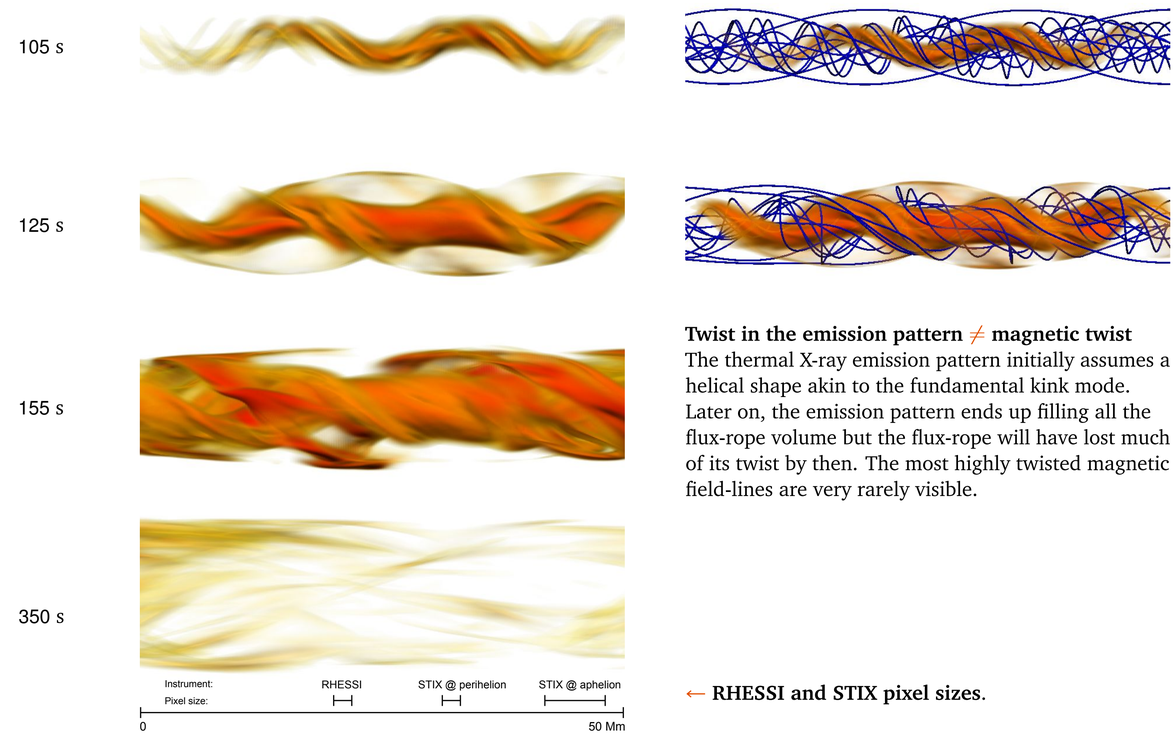
Peak amplitude: $\max(I_{h\nu}) \propto B_0^2 n_0$
Time of peak: $\tau_{peak} \propto r_0 C_a^{-1}$
(B_0: mag. field; n_0: density; r_0: radius; C_a^{-1}: Alfvén speed)

Red lines: control case with no SH conduction

6. Thermal X-ray emission morphology

Emission patterns at 5 keV
Full resolution (~ 10× RHESSI or STIX@perihelion).

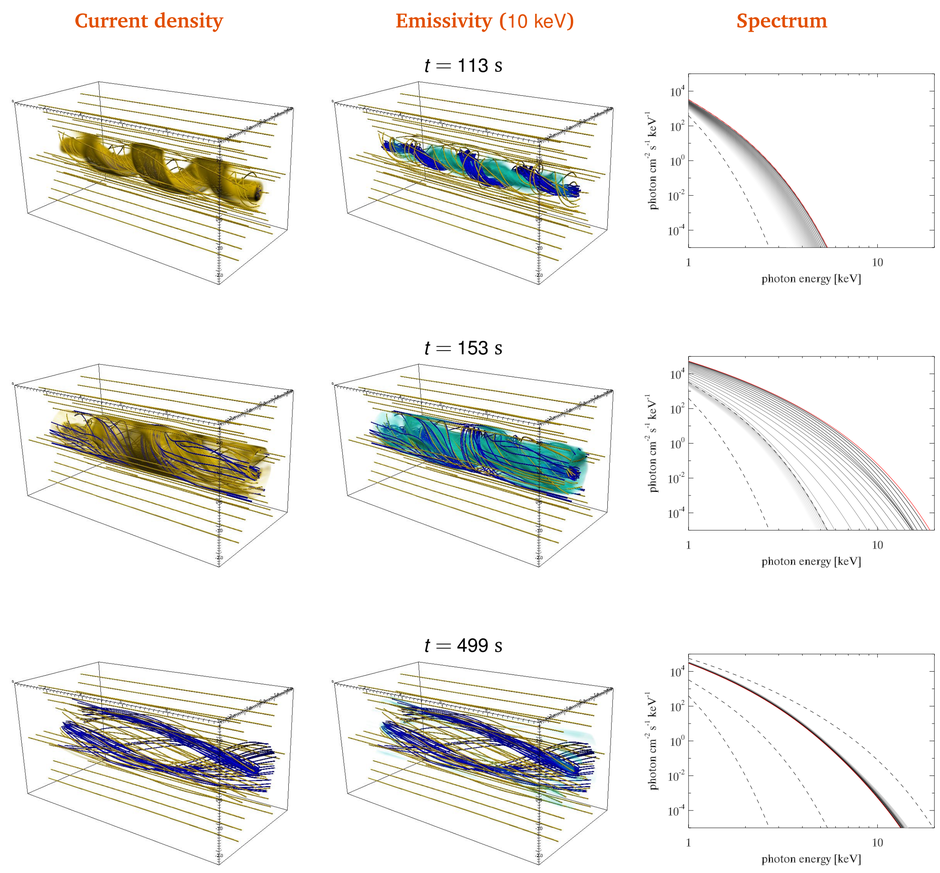
Emission patterns and **magnetic field-lines**.



Twist in the emission pattern ≠ magnetic twist
The thermal X-ray emission pattern initially assumes a helical shape akin to the fundamental kink mode. Later on, the emission pattern ends up filling all the flux-rope volume but the flux-rope will have lost much of its twist by then. The most highly twisted magnetic field-lines are very rarely visible.

← **RHESSI and STIX pixel sizes.**

7. Spectra



Linear phase
Triggering of the kink instability.
A helical current sheet forms around the flux-rope's boundary.
Moderate heating (mostly by compression).

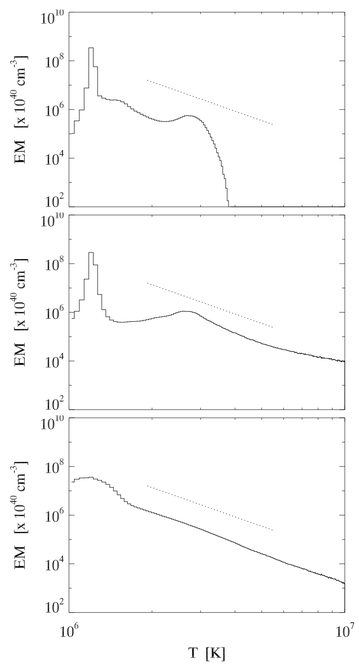
Saturation
The flux-rope reconnects with the background field.
Strong and quick ohmic heating, leading to a harder thermal spectrum.
The emitting region becomes thicker.

Relaxation phase
The flux-rope relaxes towards a lower energy state, with a minimal amount of twist.
Emission concentrates into filamentary patterns and fades away. The spectrum slowly decays at all energies, but without becoming as soft as initially for a long period of time.

Temporal evolution of the magnetic field, of the current density amplitude, of the emissivity at 10 keV and of the total emission spectrum. The red lines show the spectra at the same instants as the figures to the left, and the light to dark grey show spectra at some preceding instants (hence giving an idea of the quickness of the evolution of the spectra).

8. Light-curves, multi-temperature plasma

EM vs. T



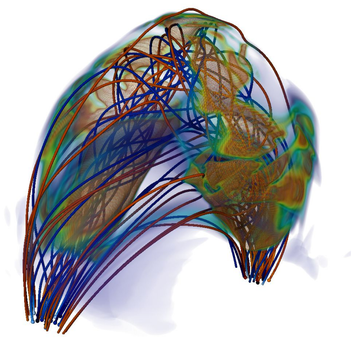
Emission measure (EM) vs. temperature.
(EM: "quantity of plasma" emitting at a given temperature)

$t = 0$ s: Dirac-δ at $T = 1.2 \times 10^7$ K
$t \leq 100$ s: Upper tail forms
$t \geq 125$ s: Strong ohmic heating → "bump" in T
$t >> 500$ s: **Power-law** $EM \propto T^{-4.2}$ (for $T \gtrsim 2 \times 10^6$ K)

9. Future work

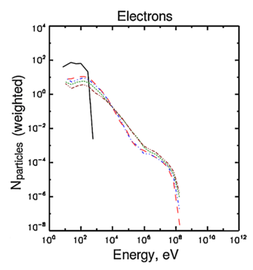
Future work

Curved loops + background stratification



Photon flux at 3 keV in a curved twisted flux-rope.

Hard X-ray emission



(Gordovskyy et al., 2013)

Hard X-ray emission deduced from test-particle trajectories and collisions rates (with stratified background plasma)

10. Conclusions and future work

- We have estimated the continuum thermal X-ray emission from MHD simulations of flaring coronal loops.
- Our results are in agreement with several observational properties of solar flares, despite the simplicity of the model..
- The computed spectra reveal the formation of a multi-temperature plasma, as in observed flares. Strong ohmic diffusion leads to a quick hardening of the spectra.
- The light-curves for lower energy bands decay more slowly than higher energy ones.
- We found that the emission measure and temperature scale as $EM \propto T^{-4.2}$ (asymptotically).
- Future work: Inclusion of the chromospheric layers, so as to analyse the dynamical consequences of the enhanced heat deposition in the dense lower layers.
  Estimation of hard X-ray emission.