The Effect of Nanoflare Heating on Coronal Spectral Lines

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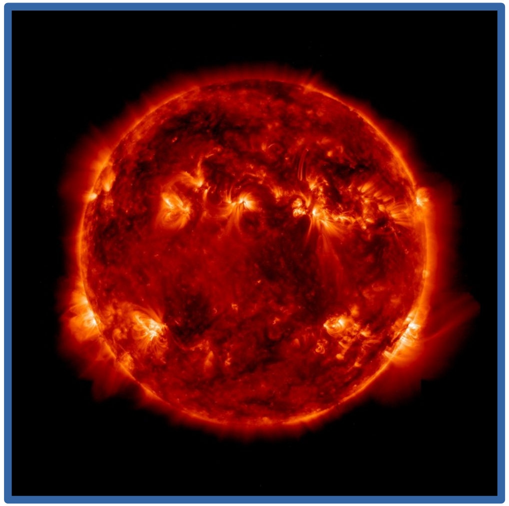
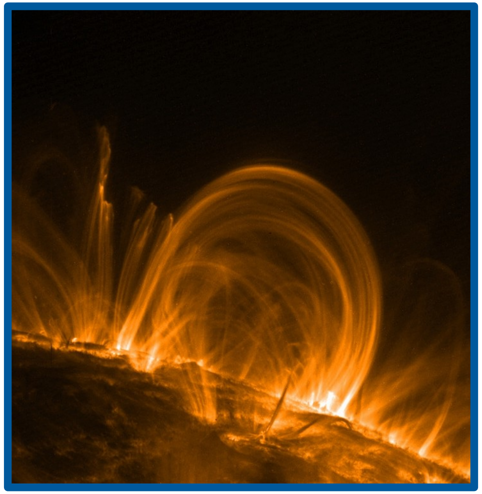
The Solar Corona



Coronal heating continues to be one of the unsolved problem of Astrophysics.

It is widely accepted that the mechanism must be of magnetic origin.

Despite the variety of models proposed, a definitive answer to what is the precise process is still due.



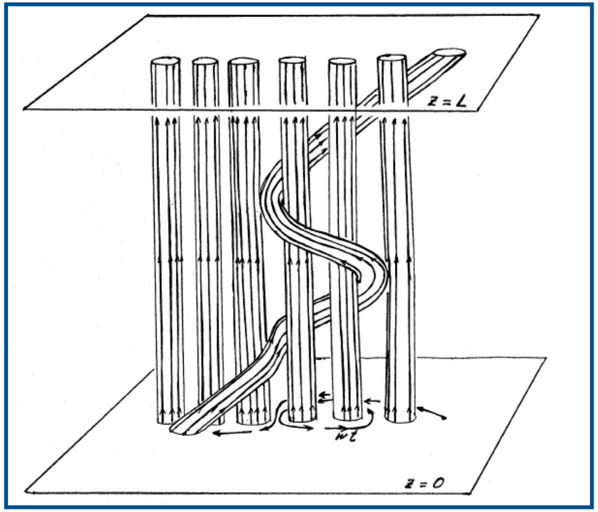
Due to its high conductivity and low β, the coronal plasma is obliged to flow along magnetic field lines.

For this reason, the corona is structured in the form of loops that follow the spatial configuration of the field.

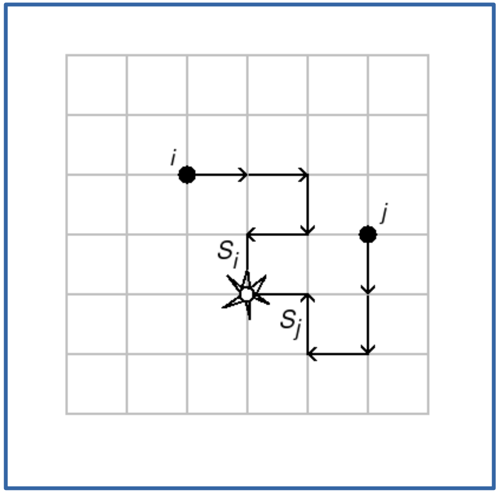
Any model proposed to explain coronal heating must be consistent with the observed characteristics of these loops.

Nanoflare heating model

One of the most popular theories of coronal heating is based on the production of so-called nanoflares (Parker 1988, ApJ, 330, 474):



⁕ Loops are formed by elementary sub-resolution magnetic strands.
⁕ Magnetic stress between neighbor strands is injected by the convective displacements of their photospheric footpoints.
⁕ When a certain threshold (critical inclination angle) is reached, strands reconnect producing a nanoflare.

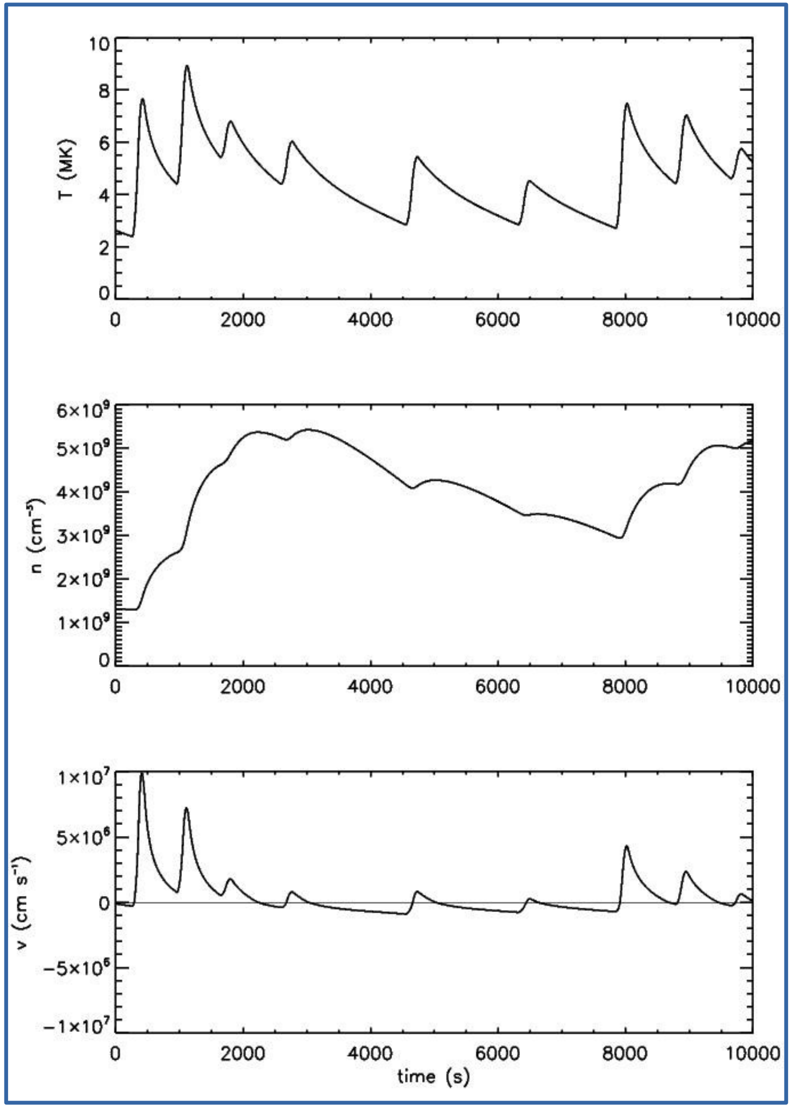


We developed a model based on cellular automata that simulates the scheme proposed by Parker (López Fuentes & Klimchuk 2015, ApJ, 799, 128). It consists of a set of points that move around and interact in a 2D mesh. Interactions in the presence of a critical condition lead to the onset of nanoflares.

Plasma evolution

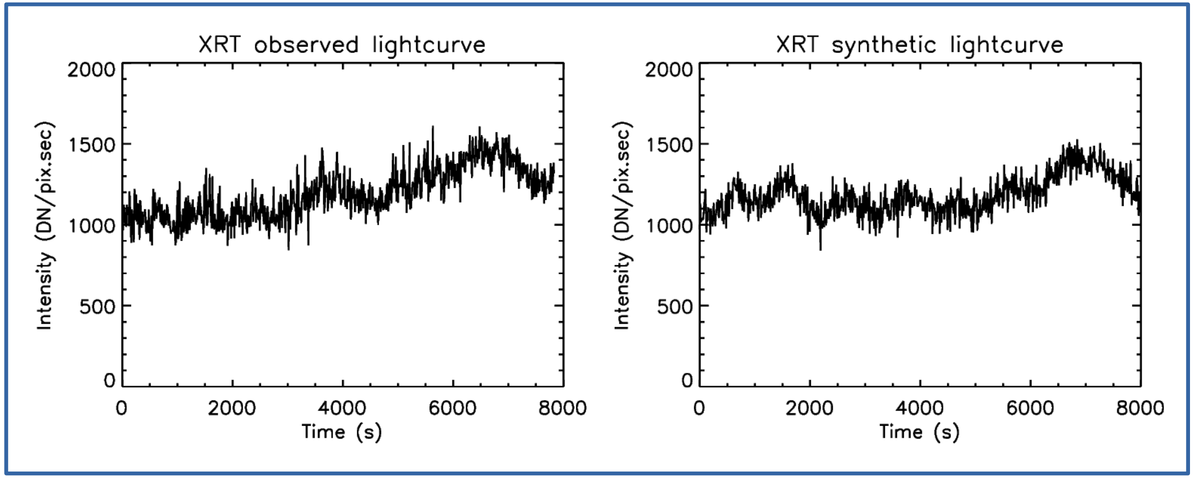
We model the plasma evolution on each strand using the EBTEL model (*Enthalpy Based Thermal Evolution of Loops,* Klimchuk et al., 2008, ApJ, 682, 1351)

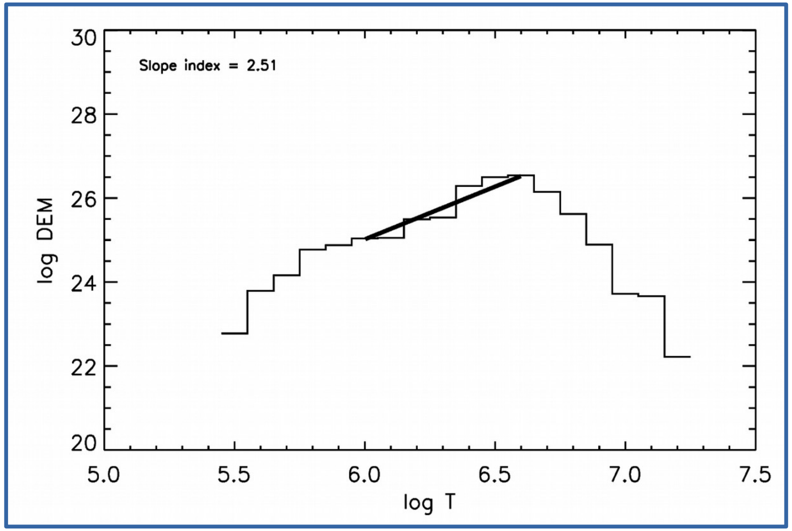
The plots show the evolution of the mean temperature, density and velocity of the plasma in a magnetic strand over 10^4 s.



Model results

The model reproduces the main statistical properties of observed loop lightcurves (Hinode/XRT, SDO/AIA, López Fuentes & Klimchuk 2016, ApJ, 828, 86)





It also reproduces the characteristics of emission measure distributions obtained from coronal loop observations (see e.g., Schmelz & Pathak 2012; Bradshaw et al. 2012).

The nanoflare energies produced by the model follow power-law distributions with typical indexes around -2.5.

Coronal flows

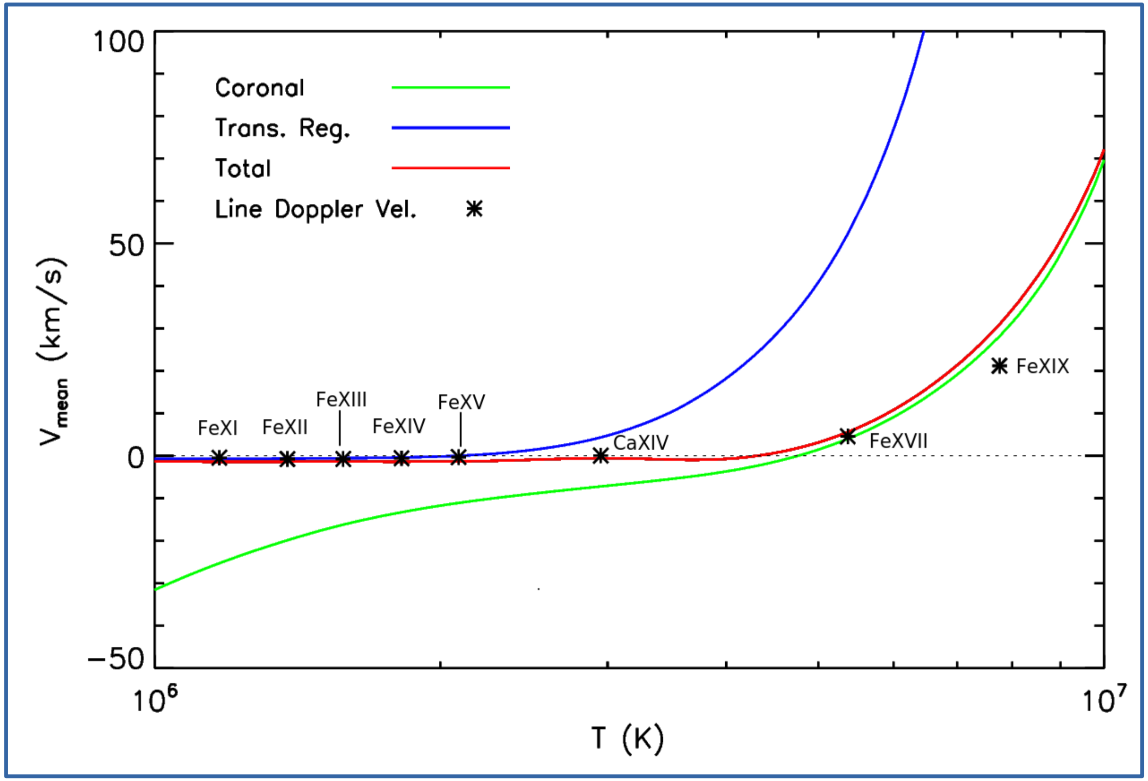
The nanoflare model predicts the presence of plasma flows along the loops. Different works, using spectrographs such as the *EUV Imaging Spectrometer (EIS)* on board *Hinode* have detected the presence of flows (see e.g., Young et al. 2012, Warren et al. 2011, Tripathi et al. 2012, Winebarger et al 2013). Downflows between 5 and 40 km/s are observed in the 0.5 to 2 MK range.

Using our model for a loop of 100 Mm length and 49 strands, we compute the EM weighted mean velocity as a function of temperature:

$$V_m(T) = \frac{\int DEM(T)V(T)dt}{\int DEM(T)dt}$$

The obtained coronal velocities coincide in magnitude with observations.

The Transition Region contribution produces much smaller weighted velocities for the cooler temperature range.



Spectral line simulations

We construct synthetic spectral lines by summing up the coronal intensity contribution of each strand at each time step of the program, *t*:

$$I_j(t) = n^2(t)G_i(T(t))$$

and we integrate it over an observation time *Δt*. $G_i(T)$ is the Ion contribution function obtained from CHIANTI

The contribution of each strand at each instant is modeled with a gaussian distribution of width:

$$w = \frac{\lambda_0}{c}\left(\frac{2kT}{m_i}\right)^{\frac{1}{2}}$$

Centered at:

$$\lambda_D(t) = \frac{\lambda_0}{\left(1 + \frac{V(t)}{c}\right)}$$

(λ_0 = line center at rest)

We compute the transition region (TR) contribution intensity as

$$I_{TR} = \int_{T_b}^{T_0} DEM_{TR}(T)G(T)dT$$

The lines are modeled as above and both contributions are added.

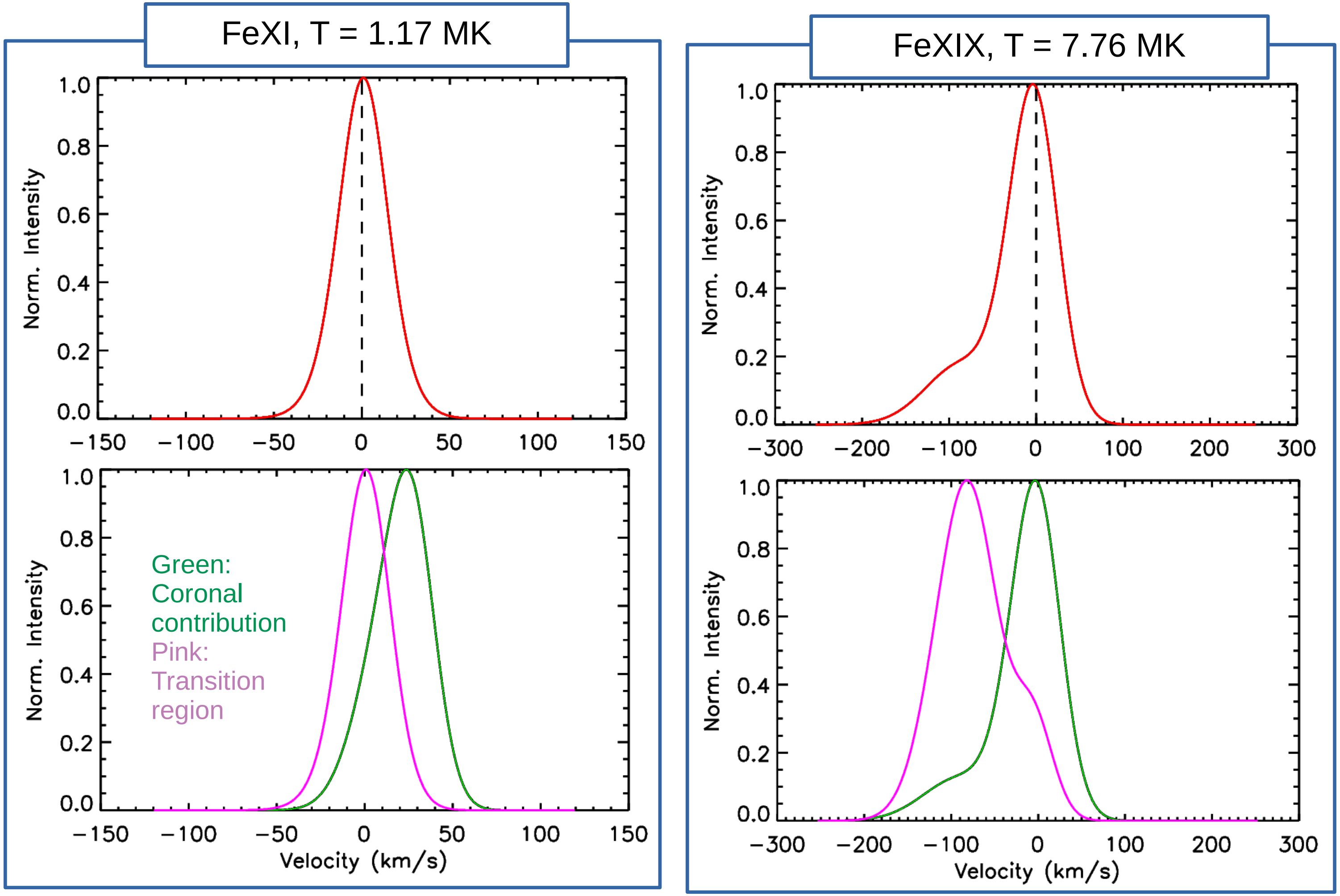
Examples

The TR component provides velocities that are much smaller than their coronal counterparts.

For the colder lines (T < 1MK) the TR intensity is much higher.

Wavelengths are transformed in velocities using:

$$V = c\,(1 - \lambda_0 / \lambda)$$



Line characterization

To compare with observations we compute the moments of the modeled lines:

$$M_1 = \frac{\int \lambda I(\lambda) d\lambda}{\int I(\lambda) d\lambda}$$

$$M_2 = \frac{\int (\lambda - M_1)^2 I(\lambda) d\lambda}{\int I(\lambda) d\lambda}$$

M_1 provides the Doppler displacement of the line: $\Delta\lambda_D = M_1 - \lambda_0$, and the Doppler velocity: $V_D = c\, \Delta\lambda_D / M_1$

M_2 provides the non-thermal velocity ξ, from: $M_2 = \frac{\lambda^2}{2c^2}\left(\frac{2kT}{m_i} + \xi^2\right)$

Where $V_0 = \left(\frac{2kT}{m_i}\right)^{\frac{1}{2}}$ is the thermal component

Results

We characterized 11 modeled lines within the spectral range of *Hinode/EIS*

Integration over 30 s for a model with L = 100 Mm and 49 strands.

Ion	T (MK)	λ0 (Å)	ΔλD (Å)	VD (km/s)	V0 (km/s)	ξ (km/s)	TR/Cor
FeVIII	0.417	194.66	1.53E-04	0.23	11.12	13.83	1059.40
SiVII	0.589	275.35	6.41E-04	0.70	18.60	20.63	499.74
FeX	0.977	184.54	3.20E-04	0.52	17.03	19.37	65.88
FeXI	1.17	188.23	2.90E-04	0.46	18.63	21.48	42.27
FeXII	1.38	195.12	4.88E-04	0.75	20.24	23.36	22.62
FeXIII	1.58	202.04	5.04E-04	0.75	21.65	25.13	11.26
FeXIV	1.82	274.2	5.19E-04	0.57	23.24	27.20	6.02
FeXV	2.09	284.16	3.05E-04	0.32	24.91	30.15	2.86
CaXIV	2.95	193.87	-4.58E-05	-0.07	34.86	39.66	1.01
FeXVII	5.37	254.35	-3.89E-03	-4.58	39.92	44.69	0.19
FeXIX	7.76	592.24	-4.19E-02	-21.21	47.99	65.22	0.05

Doppler velocities

Our model comprises a range of nanoflare frequencies (see López Fuentes & Klimchuk 2016).

In order to study how different nanoflare frequencies affect the results, we integrate spectral lines along strands with different nanoflare repetition times.

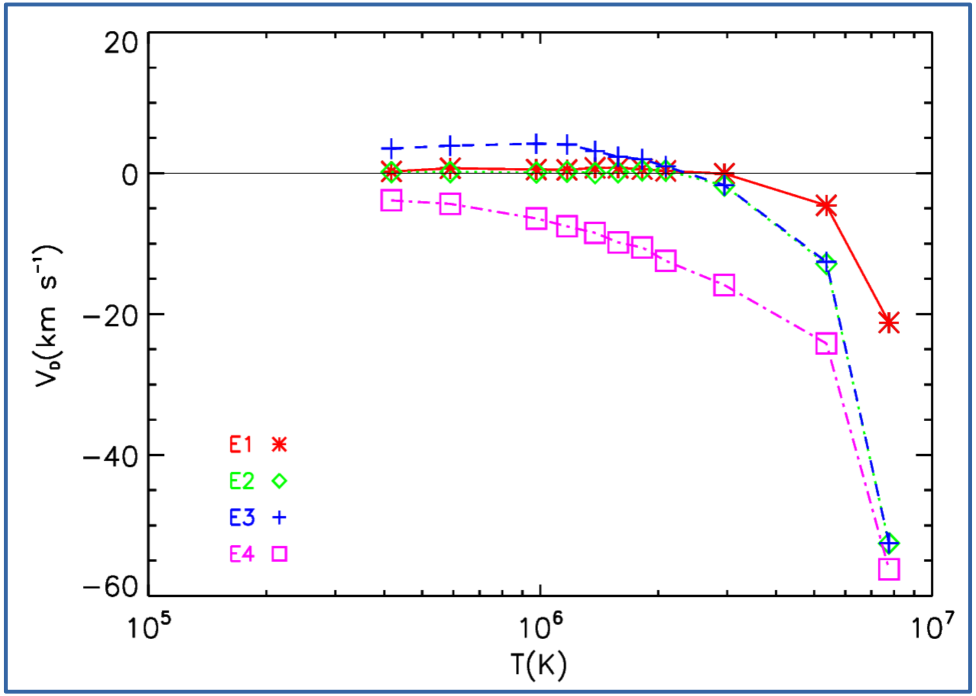
The plot shows Doppler shift velocities in function of temperature, obtained from modeled lines for the elements listed in the previous table.

E1: Line simulations for CA-EBTEL combination – 49 strands.

E2: Single nanoflare evolution, total energy: 5 erg (typical energy in our multistrand model), nanoflare duration: 200 s, repetition time: 3000 s (mid-frequency nanoflares)

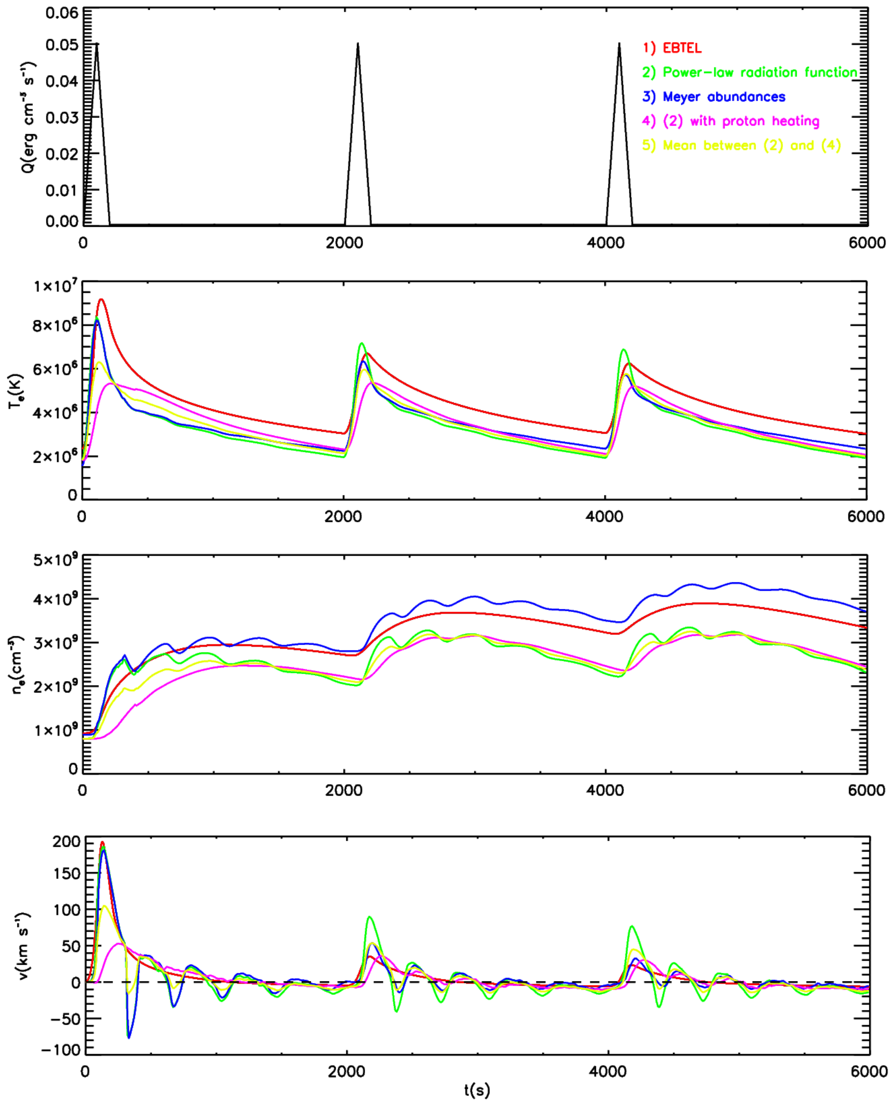
E3: Same as E2, for a repetition time of 5000 s (low-frequency nanoflares)

E4: Same,for a repetition time of 1000 s (high-frequency nanoflares in our model)



Results using HYDRAD

In order to validate our model results we are presently comparing EBTEL nanoflares with the Hydrodynamic and Radiation code (HYDRAD, see e.g., Bradshaw & Klimchuk 2011).



Conclusions

- We constructed synthetic spectral lines from plasma temperatures, densities and velocities obtained with our coronal heating model based on nanoflares.
- We included the contribution of the Transition Region emission and found that it predicts smaller velocities than its coronal counterpart.
- We studied the effect of different nanoflare frequencies and found it consistent with our results.
- Presently, we are validating the results of our model with a more sophisticated (and computer time consuming!) 1D hydrodynamic model (HYDRAD, see Bradshaw & Cargill, 2013).