Flare energetics deduced from X-ray observations: considering some caveats

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Study of Warmuth & Mann (2016a/b)

- 24 flares from C3 to X17
- time series of GOES fluxes and RHESSI spectra (isotherm. + CTTM)
- time series of HXR images: source sizes (Warmuth & Mann 2013a,b)
- nonthermal electron input: 

\[ P_{nth}(t) = \int_{E_{LC}}^{E_{HC}} dE \ F_0(E,t) \cdot E \]

- thermal energy: 

\[ E_{th}(t) = 3 k_b T \sqrt{EM \cdot V} \]

- radiative loss rate: 

\[ P_{rad}(t) \quad \text{(from CHIANTI)} \]

- conductive loss rate: 

\[ P_{cond}(t) \sim A_{FP} \cdot T^{7/2} \cdot l^{-1} \quad \text{(Spitzer, with saturation)} \]

- total heating requirement: 

\[ E_{th,tot} = \int_{t_B}^{t_E} dt \left( \frac{dE_{th}(t)}{dt} + P_{rad}(t) + P_{cond}(t) \right) \]
Results of Warmuth & Mann (2016a/b)

- two thermal components: 10-25 MK (evaporated), > 25 MK (directly heated)
- total energy requirements of hot plasma ~ bolometric energy
- conductive losses are a major contribution
- nonthermal energy input ~ bolometric energy only in large flares
- conduction is required as additional heating mechanism of dense lower atmosphere
Results of Warmuth & Mann (2016a/b)

\[ \alpha_{nth}: 1.09 \pm 0.08 \]
\[ \alpha_{th}: 0.73 \pm 0.05 \]
\[ \alpha_{bol}: 0.79 \pm 0.10 \]
Consider some caveats…

**nonthermal component:**
- low-energy cutoff
- energy input by protons

**thermal component:**
- potential energy and kinetic flow energy plasma
- filling factor
- temperature gradient for conductive losses
- conductive losses as gains (reprocessing)
- multithermality
Nonthermal energy input

- **Electrons:**
  - low-energy cutoff usually masked by thermal emission
  - highest low-E cutoff consistent with spectra
    → lower estimate for injected electron flux and power

- **Ions:**
  - energy in >1 MeV ions broadly comparable to energy in electrons
    (but large uncertainties)
  - no constraints on energy in low-energy ions
Baseline

\[ \alpha_{\text{nth}}: 1.09 \pm 0.08 \]
\[ \alpha_{\text{th}}: 0.73 \pm 0.05 \]
\[ \alpha_{\text{bol}}: 0.79 \pm 0.10 \]
Low energy cutoff: 20 keV

\[ \alpha_{\text{nth}}: 1.34 \pm 0.12 \]
\[ \alpha_{\text{th}}: 0.73 \pm 0.05 \]
\[ \alpha_{\text{bol}}: 0.79 \pm 0.10 \]
Low energy cutoff: 10 keV

\[ \alpha_{\text{nth}}: 1.49 \pm 0.21 \]
\[ \alpha_{\text{th}}: 0.73 \pm 0.05 \]
\[ \alpha_{\text{bol}}: 0.79 \pm 0.10 \]
Summary on nonthermal input

• Electrons:
  - low-energy cutoff ~10 keV required to account for thermal component in small flares
  - this steepens power-law
    → inconsistent with bolometric energy in strong flares

• Ions:
  - weak flares would require 10x more energy in ions than in electrons
    → inconsistent with observations

• Conclusion:
  additional non-beam heating mechanism required
Potential and flow energy

- potential energy negligible (1% of thermal energy)
- flow energy <10% of thermal energy for 200 km/s (equipartition for 700 km/s)
Filling factor of thermal and nonthermal sources

- volume filling factor of coronal source influences thermal energy
  - EUV observations suggest small filling factors \( f_v < 0.1 \)
  - X-ray observations suggest larger values \( f_v = 0.1-1 \)
  - constraints by density-sensitive lines and plasma beta

- area filling factor of HXR FPs influence conductive loss
  - HXR FP area taken as thermal loop FP area
  - is this a valid assumption?
  - RHESSI imaging reaches limits for compact FPs
  - observation of compact WL kernels
    \( \rightarrow \) real FP areas smaller \( f_A < 1 \)
Baseline

\[ \alpha_{\text{nth}}: 1.09 \pm 0.08 \]
\[ \alpha_{\text{th}}: 0.73 \pm 0.05 \]
\[ \alpha_{\text{bol}}: 0.79 \pm 0.10 \]

- nonthermal energy (electrons)
- total thermal requirements (incl. losses)
- bolometric energy (Emslie et al. 2012)
- bolometric energy (Kretzschmar 2011)
Filling factor: $f_V = 0.1$, $f_A = 0.1$

\begin{itemize}
\item\(\alpha_{nth}: 1.09\pm0.08\)
\item\(\alpha_{th}: 0.95\pm0.06\)
\item\(\alpha_{bol}: 0.79\pm0.10\)
\end{itemize}
Influences on conductive losses

- loop FP areas

- conductive losses $\sim$ thermal gradient $\sim$ thermal scale length

- partial ‘recycling’ of conductive losses
  - losses can drive chromospheric evaporation, increasing amount of hot plasma
  - reduces nonthermal energy input requirements

- suppression of conduction by turbulence (cf. talk by Emslie)
Baseline: temperature scale length = loop half-length

\[ \alpha_{\text{nth}}: 1.09 \pm 0.08 \]
\[ \alpha_{\text{th}}: 0.73 \pm 0.05 \]
\[ \alpha_{\text{bol}}: 0.79 \pm 0.10 \]
Temperature scale length: 10 Mm

$\alpha_{nth}: 1.09 \pm 0.08$

$\alpha_{th}: 0.80 \pm 0.05$

$\alpha_{bol}: 0.79 \pm 0.10$
Temperature scale length: 1 Mm

\[ \alpha_{n\text{th}}: 1.09 \pm 0.08 \]
\[ \alpha_{t\text{h}}: 0.74 \pm 0.05 \]
\[ \alpha_{b\text{oi}}: 0.79 \pm 0.10 \]
Baseline

\[ \alpha_{\text{nth}}: 1.09 \pm 0.08 \]
\[ \alpha_{\text{th}}: 0.73 \pm 0.05 \]
\[ \alpha_{\text{bol}}: 0.79 \pm 0.10 \]
Fraction of conductive loss that is recycled: 0.5

\[ \alpha_{nth} = 1.09 \pm 0.08 \]
\[ \alpha_{th} = 0.78 \pm 0.06 \]
\[ \alpha_{bol} = 0.79 \pm 0.10 \]
Fraction of conductive loss that is recycled: 0.9

\[ \alpha_{\text{nth}}: 1.09 \pm 0.08 \]
\[ \alpha_{\text{th}}: 0.92 \pm 0.06 \]
\[ \alpha_{\text{bol}}: 0.79 \pm 0.10 \]
Summary on conductive losses

- **Lower conductive losses**
  - by reducing FP area, recycling
  → would require additional energy release or transport process to heat lower atmosphere

- **Higher conductive losses:**
  - by decreasing thermal scale length
  → inconsistent with bolometric energy loss
Multithermality

• have considered RHESSI and GOES
  → bithermal model for hot plasma component

• difference to bolometric energy shows the strong contribution of cooler plasma

• comparison with true multithermal results (EUV-based DEM reconstructions)
Thermal energies: multithermal (EUV) vs. isothermal/bithermal (X-rays)

\[ \alpha_{\text{AIA}}: \ 1.06 \pm 0.06 \]
\[ \alpha_{R+G}: \ 0.87 \pm 0.06 \]
\[ \alpha_R: \ 0.78 \pm 0.07 \]
\[ \alpha_C: \ 0.74 \pm 0.09 \]
\[ \alpha_{\text{bol}}: \ 0.79 \pm 0.10 \]
Conclusions

- energy requirements of hot plasma can be brought down to be consistent with nonthermal energy input
  \[\rightarrow \text{inconsistent with bolometric energy (too little energy input into low atmosphere)}\]

- nonthermal energy input can be increased to match heating requirements only by making ad-hoc assumptions

- additional non-beam heating mechanism required

- strong conductive losses of hot plasma required