Plasma Heating During Coronal Mass Ejections

Nick Murphy,[1] John Raymond,[1] Cara Rakowski,[2]
Kathy Reeves,[1] Kelly Korreck,[1] & Trae Winter[1]

[1]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
[2]Naval Research Laboratory, Washington, D.C., USA

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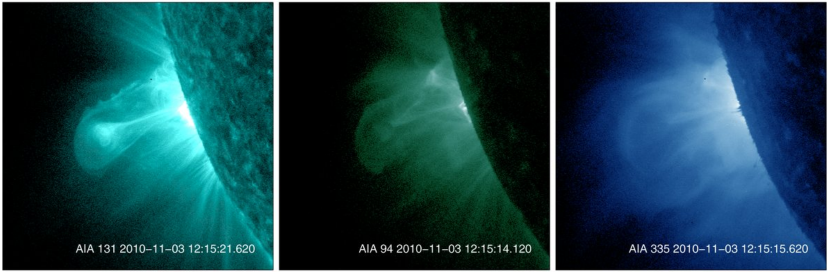
Outline

- Observational evidence for heating of CME plasma
- Non-equilibrium ionization modeling of CMEs
- Candidate heating mechanisms
- Future instrumentation

Introduction

- To understand astrophysical phenomena, we must understand the energy budget
- Magnetic energy dominates CMEs but is difficult to diagnose in the corona
- The kinetic and potential energies are estimated using white light coronagraphs
- This talk focuses on thermal energy and plasma heating during CMEs

The 2010 Nov 3 CME observed by SDO/AIA shows evidence for a hot core



Reeves & Golub (2011)

- Emission in 94 & 131 channels not present in cooler channels indicates a core temperature of 5–10 MK and early heating

Key Questions

- How much is CME plasma heated?
- What are the spatial and temporal dependences of heating?
- How does flare magnitude correlate with CME heating properties?
- What physical mechanisms are responsible for heating?
- Where does the energy for CME heating come from?
- What are the consequences of CME heating on magnetic cloud propagation and space weather?

There are three main strategies for constraining CME heating rates

- Ultraviolet spectroscopy (e.g., Akmal et al. 2001)
  - *Hinode*/EIS, *SOHO*/UVCS
- *In situ* charge state observations (e.g., Rakowski et al. 2007)
  - *ACE*, *Wind*, *STEREO*, *Ulysses*
- Multiwavelength EUV and X-ray imaging
  - *Hinode*/XRT, *SDO*/AIA, *STEREO*/EUVI, *SOHO*/EIT
- For quantitative constraints, all three techniques usually require non-equilibrium ionization modeling

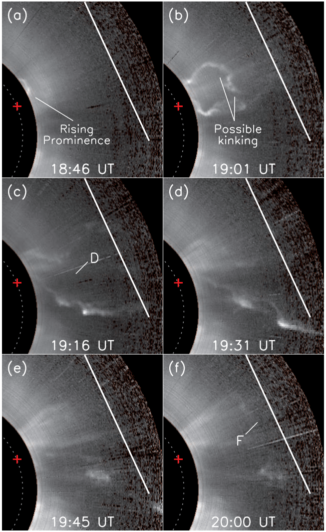
Non-equilibrium ionization modeling is required when ionization/recombination timescales $\lesssim$ expansion timescale

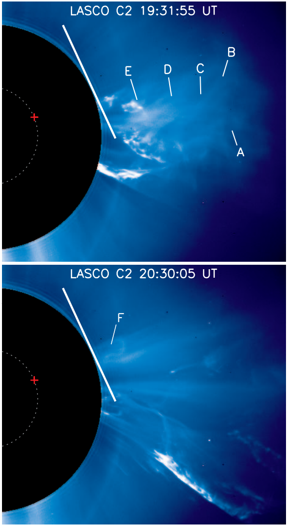
- This condition is satisfied in CMEs
- Charge states freeze in at several solar radii
- Thermal history can be inferred from charge state distribution
- Errors in atomic data $\Longrightarrow$ systematic uncertainties
- In contrast, differential emission measures (DEMs) assume ionization equilibrium but may be appropriate at low heights for slowly evolving, high density events

Non-equilibrium ionization modeling of CMEs

- Constrain densities from observations
  - EIS: several density-sensitive line ratios (Landi et al. 2010)
  - UVCS: O V line ratio (Akmal et al. 2001)
  - LASCO, MLSO/MK4: column densities (Lee et al. 2009)
- Constrain velocity history
- Find charge state distributions using UV spectroscopy, EUV imaging, or *in situ* observations
- Run a grid of time-dependent ionization models with different heating parameterizations and rates
- Models self-consistently include radiative losses, but usually assume Maxwellian temperature distributions
- The models consistent with observations provide allowed heating rates

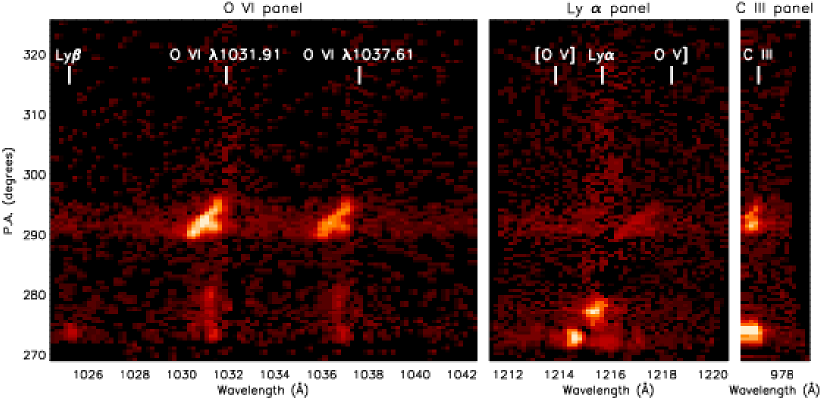
Example event: 28 June 2000 CME observed by UVCS





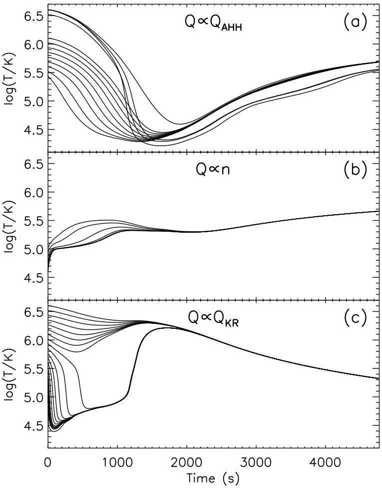
- We identify multiple features seen by UVCS in MK4 and LASCO observations (Murphy et al. 2011)

UVCS observed Ly α, Ly β, C III, O V, O VI, C II, and N III emission during this event



- Blob F appears as a diagonal shear flow feature in UVCS with weak Ly α and Ly β emission
- Density derived from O V line ratio

For well-constrained features in this and other events, cumulative plasma heating $\gtrsim$ kinetic energy



- Above: allowed temperature histories for three different heating parameterizations for blob F

Non-equilibrium ionization modeling of *in situ* observations of ICMEs also find plasma heating $\gtrsim$ kinetic energy

- Enhanced iron charge states often indicative of ICMEs (Lepri & Zurbuchen 2004)
- ICMEs contain charge states representative of $\lesssim 6 \times 10^4$ to 5×10^6 K (Gilbert et al. 2012)
- Filament material present in $\gtrsim$4% of ICMEs observed by *ACE* (Lepri & Zurbuchen 2010)
- High charge state plasma ($\mathrm{Fe}^{\geq 16+}$) sometimes trails behind flux rope (Rakowski et al. 2011)

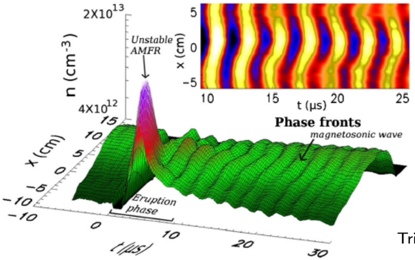
Inferred characteristics of plasma heating during CMEs

- Cumulative heating energy $\gtrsim$ kinetic energy
  - Counters rapid adiabatic cooling and radiative losses
  - Models with no heating usually inconsistent with data
- Heating is gradual and continues after initial eruption
  - Initially hot plasma that expands and cools cannot explain spectroscopic or *in situ* observations
- Heating is inhomogeneous
  - Different features have different heating rates in same event
  - UVCS observes cool emission offset from warm emission (Lee et al. 2009)
  - *In situ* detections of filament material

What mechanisms could be responsible for heating?

- The most probable mechanisms are:
  - Dissipation of waves generated by the eruption
  - Reconnection and relaxation during flux rope expansion
  - Energetic particles
  - Upflow from the CME current sheet
- Unlikely mechanisms are:
  - Thermal conduction
    - Inferred heat transfer rate too slow (Lee et al. 2009; Landi et al. 2010)
  - Shocks from colliding flows (Fillipov & Koutchmy 2002)
    - Not enough energy (Landi et al. 2010; Murphy et al. 2011)
  - Dissipation of waves generated through photospheric motions

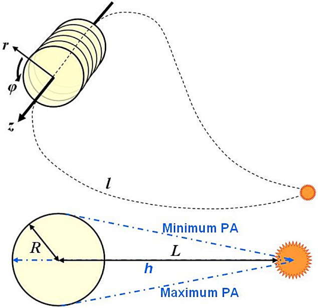
Candidate mechanism: wave heating



Tripathi et al. (2010)

- Wave heating from photospheric motions is unlikely
  - Would require photospheric motions much larger than observed and heating rates much larger than inferred for coronal holes (Landi et al. 2010; Murphy et al. 2011)
- Waves generated by the eruption are a possibility
  - Lab experiments of expanding flux ropes show heating by dissipation of fast magnetosonic waves (Tripathi et al. 2010)
  - Line widths can provide constraints
- Resonant absorption of Alfvén waves could also be important (Evans et al.)

Candidate mechanism: small-scale relaxation and reconnection during flux rope expansion



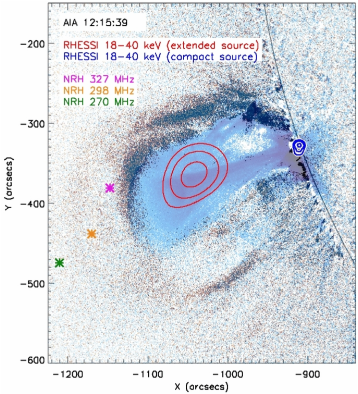
Wang et al. (2009)

- Several models have been developed to describe magnetic relaxation in expanding flux ropes (Kumar & Rust 1996, KR; Wang et al. 2009; Lyutikov & Gourgouliatos 2011, LG11)
- Common assumptions: helicity conservation, self-similarity
- Prediction: a significant fraction of lost magnetic energy goes into plasma heating

Candidate mechanism: small-scale relaxation and reconnection during flux rope expansion

- These models describe global relaxation and do not describe the dissipation mechanism in detail
- UVCS line width measurements suggest that turbulence needs to be continually replenished to explain heating
- Rakowski et al. (2011) apply LG11's expanding spheromak model
  - Good agreement with a resistivity enhancement of $\sim 10^{11}$
  - Spheromak heating unable to explain presence of $\mathrm{Fe}^{\geq 16+}$ ions
    - Additional heating mechanism needed?
- The kink instability may also play a role
  - Akin to tokamak sawteeth where kinking drives reconnection
- Simulations are needed to investigate the physics of relaxation during flux rope expansion

Candidate mechanism: Coulomb collisions between energetic particles and thermal plasma



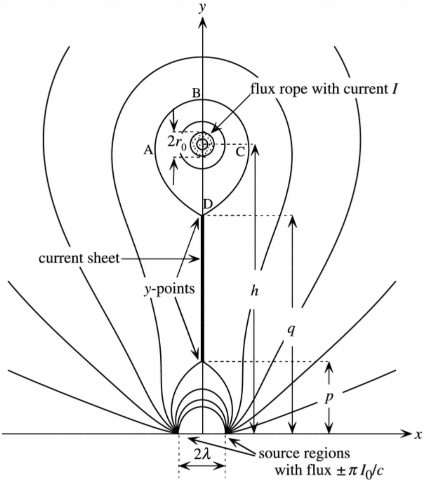
Bain et al. (2012)

- Glesener et al. find extended RHESSI emission coincident with hot flux rope in 2010 Nov 3 event
- Their analysis suggests that energetic particles caused heating

Candidate mechanism: Coulomb collisions between energetic particles and thermal plasma

- Prediction: heating is correlated with HXR emission and stops when collisions become unimportant
- Important questions:
  - What are the sources of non-thermal particles?
  - How efficient is particle transport out of flux rope?
  - Is there enough energy?
  - Is there enough time?
- Important caveat: non-thermal tail increases ionization rates

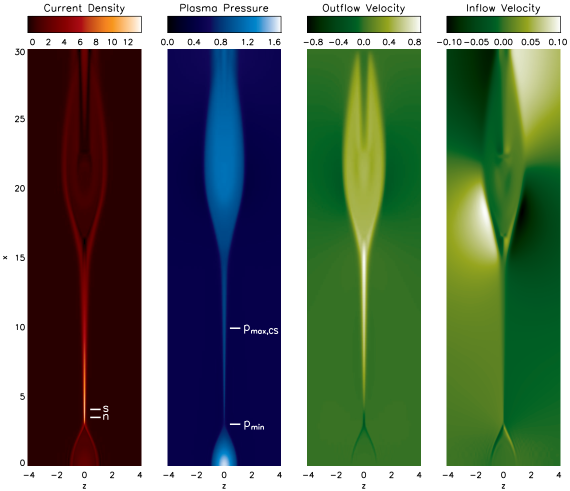
Candidate mechanism: CME current sheet upflow



Lin & Forbes (2000)

- Flux rope models of CMEs predict the formation of an elongated current sheet behind the rising plasmoid
- Reconnection upflow could heat the ejecta

Candidate mechanism: CME current sheet upflow



- 2D simulations suggest that the X-line is low
  - Murphy (2010); Reeves et al. (2010); Roussev et al. (2001)
- Most of the kinetic and thermal energy goes up

Candidate mechanism: CME current sheet upflow

- Prediction: hot plasma surrounding or trailing main flux rope
  - Source of highly ionized iron trailing the flux rope not obtained by expanding spheromak model?
- Questions:
  - How effective is mixing?
  - Is there enough energy?
  - Consequences of patchy 3D reconnection?
  - What happens when outflow is slower than flux rope?
    - Kliem: hot cores may only happen when reconnection upflow catches up with flux rope

What limits our understanding of CME heating?

- Insufficient constraints!
- Selection bias from observational techniques
  - UVCS temperature coverage best at cooler to transition region temperatures
  - AIA temperature coverage best for $1 \lesssim T \lesssim 10$ MK
- Lack of magnetic field diagnostics for coronal eruptions
- Lack of detailed theoretical predictions that distinguish between heating mechanisms
- Systematic uncertainties in atomic rates

Progress with current and future instrumentation

- Requirements: density, velocity, and charge state information
- Coordinate observations of promising active regions near limb
  - Use EIS, AIA, XRT, MK4, *RHESSI*, and *STEREO* to get conditions near Sun
  - Include *in situ* observations from *STEREO*
  - Might also provide further current sheet observations
- The Coronal Physics Investigator (CPI) on *ISS* will be a next generation UV coronagraph spectrometer (in phase A)
- EUV coronagraphs would constrain dynamics and thermal properties outside AIA's field of view
  - Broad temperature range would be helpful
- High dynamic range HXR observations (e.g., FOXSI) to constrain energetic particle properties
- Improved atomic data to reduce systematic errors

Conclusions

- Plasma heating enters into the energy budget at about the same order as the kinetic energy
- The heating is gradual and inhomogeneous
- The cause of the heating is not understood, but candidate mechanisms include:
    - Waves excited by the eruption
    - Small-scale relaxation and reconnection
    - Deposition of energy from nonthermal particles
    - Upflow from the CME current sheet
- Knowledge of CME heating arises from a combination of UV spectroscopy, *in situ* observations, and EUV/X-ray imaging
- Current observational capabilities, as well as future instrumentation, will allow further progress on this problem