Plasma Heating During Coronal Mass Ejections

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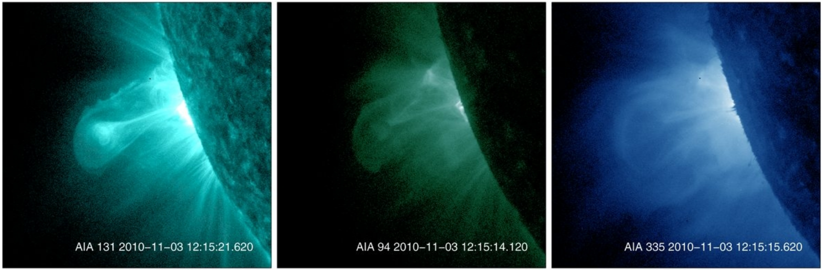
SHINE Conference 2016
Santa Fe, New Mexico, USA
July 11–15, 2016

Introduction

- Our understanding of astrophysical phenomena begins with the energy budget
- Magnetic energy dominates coronal mass ejections (CMEs) but is difficult to diagnose remotely
- CME kinetic and potential energies are estimated using white light coronagraphs (e.g., SOHO/LASCO)
- Estimates of the thermal and cumulative heating energy require non-equilibrium ionization (NEI) modeling
- We present work in progress to model the evolution of charge states during CMEs to determine heating rates in events observed by the Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO

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?
- What physical mechanisms are responsible for CME heating?
- Where does the energy for CME heating come from?
- What are the consequences of CME heating on magnetic cloud propagation and space weather?
- Are some parts of CME plasma not heated?

Candidate CME heating mechanisms (e.g., Murphy et al. 2011)

- Magnetic reconnection in the CME current sheet
- Relaxation and reconnection inside expanding flux rope
- Dissipation of Alfvén waves and turbulence
- Collisions between thermal plasma and flare-accelerated electrons
    - 2010 Nov 3 event described by Glesener et al. (2013)
- Shocks

There are three main strategies for observationally constraining plasma heating in CMEs

- **Ultraviolet spectroscopy**[1]
  - Observations from the low corona to heights of a few solar radii
  - Usually requires NEI forward modeling
  - Example instruments: SOHO/UVCS, Hinode/EIS
- **In situ charge state observations at 1 AU**[2]
  - Requires NEI modeling
  - Example spacecraft: ACE, Wind, STEREO, DSCOVR
- **Multiwavelength EUV and X-ray imaging**[3]
  - Observations at the low corona
  - Example instruments: SDO/AIA, Hinode/XRT, SOHO/EIT, STEREO/EUVI, PROBA2/SWAP
  - Sometimes requires NEI modeling

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[1] Akmal et al. (2001); Landi et al. (2010); Murphy et al. (2011)

[2] Rakowski et al. (2007, 2011); Lepri et al. (2012)

[3] Cheng et al. (2011); Nindos et al. (2015)

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

- The evolution of charge states in an NEI plasma is given by

$$\frac{\mathrm{d}f_i}{\mathrm{d}t} = n_e \left[C_{i-1} f_{i-1} - \left(C_i + R_i \right) f_i + R_{i+1} f_{i+1} \right] \tag{1}$$

  where f_i is the ion fraction, n_e is the electron density, and C_i and R_i are the ionization and recombination rate coefficients for an ion with charge state i
- The thermodynamic history of NEI plasma is encoded in the charge state distributions
- Errors associated with NEI modeling include uncertainties in atomic rates ($\sim$10–30%) and the assumption of a Maxwellian distribution without energetic particles

SunNEI: a non-equilibrium ionization (NEI) python package in development

- Uses the eigenvalue method to solve NEI equations (Masai 1984; Hughes & Helfand 1985; Smith & Hughes 2010)
    - Reduces the NEI differential equations to matrix multiplication and exponential calculations
    - Inherently stable at long time steps
- The Python implementation is based off of Fortran routines by C. Shen et al. (2015)
- The Fortran implementation is useful for computationally intensive investigations and is available at https://github.com/ionizationcalc/time_dependent_fortran
    - Example: post-processing analysis of a 3D MHD simulation of the solar wind (C. Shen et al., submitted)
- The Python implementation allows easier analysis of 1D models that do not require significant computing time
    - Example: a grid of hundreds of 1D models
    - In development at: https://github.com/namurphy/SunNEI

SunNEI: CME heating module

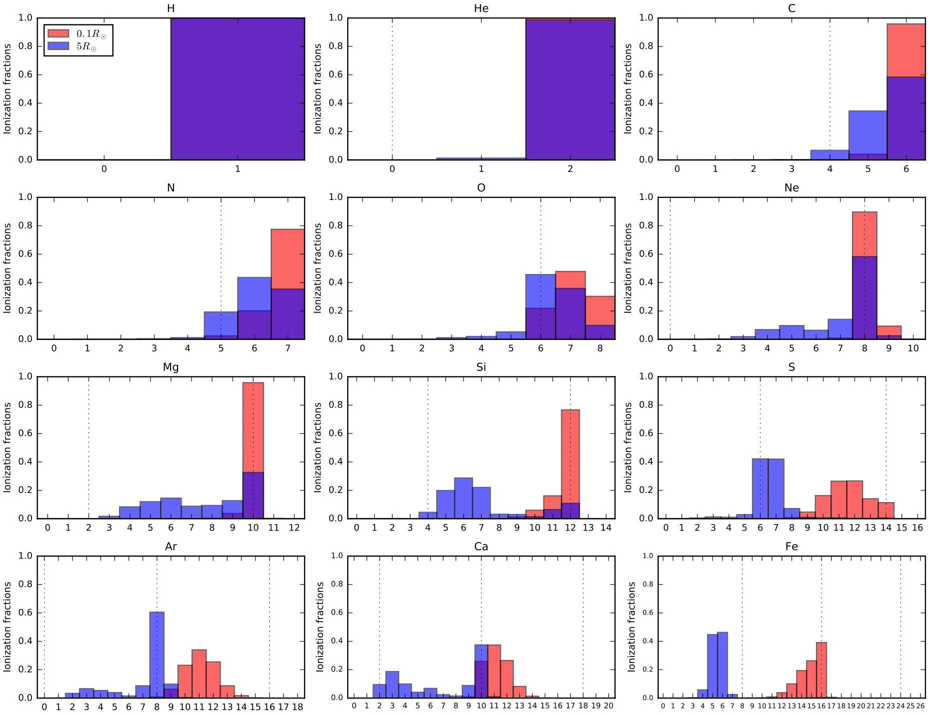
- The velocity evolution is given by

$$V(t) = V_\infty \left(1 - \mathrm{e}^{-t/\tau}\right) \tag{2}$$

  where V_∞ is the final velocity and τ is the acceleration timescale
- The density evolution is given by

$$\frac{n}{n_0} = \left(\frac{h}{h_0}\right)^\alpha \tag{3}$$

  where n_0 is the number density of neutral and ionized hydrogen at initial height above the photosphere h_0
- The temperature evolves due to adiabatic expansion and radiative cooling.
  - Next step: implementing different heating parameterizations
- Next slide: initial & final charge states for $V_\infty = 800$ km s^{-1}, $n_0 = 10^9$ cm^{-3}, $T_0 = 10^{6.4}$ K, $\alpha = -2$, and no heating


H
He
C
N
O
Ne
Mg
Si
S
Ar
Ca
Fe
$0.1R_\odot$
$5R_\odot$
Ionization fractions
0.0
0.2
0.4
0.6
0.8
1.0

Strategy for constraining heating rates for an NEI plasma

- Choose CMEs with appropriate observational constraints like
  - SOHO/UVCS observations at several solar radii
  - In situ observations at 1 AU
- Perform a grid of models based on the CME's observed properties (velocity profile, inferred density, etc.) and use different heating rates and parameterizations
- Find the models that are consistent with the observed spectrum or charge state distributions
  - The remaining models will show the allowed heating rates for each parameterization

Next steps

- Code development: add heating parameterizations and prediction capabilities for UVCS and AIA observations
- Perform a baseline study for models with no heating
  - REU project underway by Remi Rimple, who is planning to present results at the AGU Fall Meeting
- Constrain heating rates for three events for which the same plasma was observed by UVCS at multiple heights
  - This analysis should provide better constraints on plasma heating further from the eruption site
- Long-term goals include non-Maxwellian distribution function capabilities (e.g., Dzifčáková et al. 2015) and photoionization (e.g., Lepri & Landi 2015)

Summary

- Plasma heating is an important component of CME energy budgets
- Diagnosing plasma heating often requires non-equilibrium ionization modeling of the erupting plasma
- We are developing a Python implementation for non-equilibrium ionization to be applied to CMEs
- We are analyzing three events observed by SOHO/UVCS at multiple heights to better constrain continued heating after the plasma leaves the eruption site