

# Heating of the Magnetically Closed Corona

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Core Team Members (on proposal):

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## 1. Work Package Description

Our work package is an ambitious, carefully planned, and closely integrated research program to make major progress on one of the most important problems in space science: the heating of the magnetically closed corona. Our immediate objectives are to determine when, where, and why impulsive heating events known as nanoflares occur, and how the plasma responds to produce the inhomogeneous thermal structure of the corona. A long-term goal is to construct physics-based models of the solar spectral irradiance, both for space weather applications and for understanding the origin and development of life throughout the universe. We use a combination of numerical simulations, theory, and observations to investigate the many physical effects and highly disparate and coupled spatial scales that are involved. Magnetic reconnection – a fundamental process – is at the heart of the problem, and by studying nanoflares, we are gaining insights into many other heliophysical and astrophysical phenomena. We support the broader Heliophysics community through our scientific advances and leadership, by training undergraduate and graduate students and postdocs, by organizing scientific meetings, by serving on committees, by developing numerical tools for community use, and by assisting instrument and mission planning.

## 2. Progress

We have made excellent progress during the reporting period as evidenced by the 12 research papers submitted and/or accepted<sup>1</sup> and the 33 presentations given. Our strategy as outlined in the proposal calls for research into the small, intermediate, and large-scale aspects of heating, all of which are crucially important. These three spatial regimes can also be thought of as individual

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<sup>1</sup> Additional papers published during the period but accepted previously are not included in the total.

current sheets, collections of multiple sheets (multi-strand), and whole active regions. We have made major advances in all three areas, as summarized below.

### **Individual Current Sheets**

We have essentially completed our study of dynamically driven currents sheets that are slowly becoming thinner. As shown in our earlier work on equilibrium (undriven) sheets, fast magnetic reconnection and explosive heating begin with the tearing instability. The growth rate of the instability varies inversely with the thickness of the sheet. Our latest work shows that fast reconnection occurs in a slowly driven sheet when the growth rate of the instability becomes comparable to the sheet thinning rate. This provides a valuable tool for predicting how much magnetic stress can be built up in a field before it is explosively released. This determines the magnitude of the event (nanoflare, CME, jet, flare, etc.). We presented these results at several meetings, and a draft paper is in the planning stages (Leake et al.).

Line tying (the pinning of magnetic field lines in the massive photospheric plasma) tends to inhibit the tearing instability and magnetic reconnection. We have essentially completed our study of these effects. Depending on the length of a field line (magnetic loop strand) relative to the wavelength of the fastest growing tearing mode, reconnection can be inhibited or prevented altogether. Shorter strands are less likely to reconnect. Also, line-tying impacts the amount of magnetic energy that can be released by reconnection if and when it does occur. A smaller fraction of the available free energy is released with shorter strands. We presented these results at several meetings, and a draft paper has been written (Daldorff et al.).

The above studies use periodic boundary conditions in three dimensions (thinning simulations) or two dimensions (line-tying simulations) and therefore the current sheet is effectively infinitely long. We made a theoretical discovery that current sheets of finite length that experience slow shearing can reach a critical shear whereupon they lose equilibrium, spontaneously collapse, and rapidly reconnect. This is an alternative pathway to reconnection onset, different from the slow thinning scenario described above. As already stated, the implications for nanoflares, CMEs, jets, flares, etc. are enormous. We published the results (Klimchuk, J. A., Leake, J. E., Daldorff, L. K. S., & Johnston, C. D. 2023, *Front. Phys.*, 11, 1198194) and presented them at several meetings.

### **Multi-Strand Simulations**

We developed a method to approximate coronal emission based on MHD simulations that do not include radiation or the physics of the connection to the lower solar atmosphere (evaporation, etc.). We applied the method to our earlier multi-strand simulation run with the ARMS code and obtained the important result that diffuse coronal emission comes from random nanoflares, while observationally distinct coronal loops come from local “storms” of nanoflares that experience collective behavior. We published the results (Klimchuk, J. A., Knizhnik, K. J., & Uritsky, V. M. 2023, *ApJ*, 942, 10) and presented them at several meetings.

We performed multi-strand simulations with the LaRe3D code that does include the physics that is missing from ARMS. We devoted considerable effort to developing a technique for imposing photospheric driving that does not suffer from the unwanted boundary condition effects that plague other simulations. We imposed more realistic flow patterns than those used in the ARMS simulation. Again, we found that observationally distinct loops come from nanoflare storms. We presented the results at meetings, and a draft paper is in the planning stages (Johnston et al.).

We developed a technique for identifying magnetic reconnection events based on abrupt changes in magnetic connectivity, and we are using it to determine the frequency of nanoflares in our new multi-strand simulations. Nanoflare frequency plays a major role in determining the spectrum of the emitted radiation, which is important for space weather because different parts of the spectrum are absorbed in different parts of the Earth's atmosphere. A draft paper is in the planning stages (Sow Mondal et al.).

### **Whole Active Region Models**

We model entire active regions using of the GX Simulator tool, which we helped develop. We recently implemented a major improvement: the ability to simulate nanoflares with different frequency and energy distributions. We published the results (Nita, G. M., Schonfeld, S., Klimchuk, J. A., et al. 2023, ApJ Supp, 267, 6). We will use the improved GX Simulator to determine quantitatively how different distributions – as well as different rules governing how the amplitude of heating depends on field strength, field line length, etc. – impact the observed properties of active regions. We will compare the predictions with actual observations.

As stated above, our long-range goal is to develop physics-based models of the solar spectral irradiance (SSI). The SSI is dominated by active regions, so active region modeling is a huge part of this. In line with our goal, and as a service to the community, we created the International Space Weather Action Team (ISWAT) S2-06 on Physical Origins of the Solar Spectral Irradiance, co- led by James Klimchuk and Sherry Chhabra. Klimchuk and Samuel Schonfeld contributed a chapter on the topic in the ISWAT mega-review (Reiss, M. A., Arge, C. N., Henney, C. J., Klimchuk, J. A., Schonfeld, S., et al. 2023, Advances in Space Research, in press). We also made initial progress in organizing our first team meeting.

### **Other**

We have made substantial progress in other areas that do not fit neatly into the three categories above but are nonetheless important parts of our holistic approach.

We completed our study of 1D hydro simulations (loop models) investigating whether impulsive nanoflare heating can produce behavior analogous to thermal nonequilibrium (TNE) in loops with steady heating concentrated at low altitudes. TNE is characterized by the formation of cold condensations and is the accepted mechanism of coronal rain and prominence formation. We found that condensations are indeed formed if the nanoflare frequency is sufficiently high and the

nanoflares occur at sufficiently low altitudes. We submitted the results to the *Astrophysical Journal* (Kucera, T. A., Klimchuk, J. A., & Luna, M. 2023, *ApJ*, submitted) and presented them at several meetings.

We also used hydrodynamic loop models to investigate how emission measure distributions and flows are affected by the cross-sectional area expansion with height (Knizhnik and Chhabra).

We performed a study of the shapes of coronal loop cross sections. Several statistical measures were applied to cross-loop intensity traces from both idealized models and high-resolution coronal observations from the Hi-C rocket experiment. We found that approximately circular cross sections are more consistent with the observations than highly non-circular cross sections. This result is consistent with our multi-strand MHD simulations, which also suggest cross sections with low eccentricity. We submitted the work to the *Astrophysical Journal* (Uritsky, V. M. & Klimchuk, J. A. 2023, *ApJ*, submitted).

We continued to investigate the properties of active regions using spectral line observations, which provide valuable constraints on our multi-strand MHD and 1D hydro models. In particular, we measured non-thermal line widths with EUNIS, EIS/Hinode, and IRIS observations and center-to-limb variations of Doppler shifts using IRIS observations. The former were presented at meetings and a paper is in the planning stages (Brosius et al.), and the latter were published (Rajhans, A., Tripathi, A., Kashyap, V. L., & Klimchuk, J. A. 2023, *ApJ*, 944, 158).

Additional results that we submitted for publication or had accepted during fiscal year 2023 include modeling X-ray bright points (mini active regions) with nanoflare heating (Mondal, B., Klimchuk, J. A., et al. 2023, *ApJ*, 945, 37), modeling coronal rain from TNE in stellar coronae (Daley-Yates, S, Jardine, M. M. and Johnston, C. D. 2023, *MNRAS*, 526, 1646), understanding the excessive emission observed at temperatures below 0.1 MK (Gontikakis, C., Antiochos, S. K. & Young, P. R., 2023, *ApJ*, 943, 120), measuring reconnection outflows (Mondal S., Uritsky V.M. 2023, *ApJ*, 2023, 953, 84), measuring the center-to-limb variation of active region Doppler shifts (Rajhans, A., Tripathi, A., Kashyap, V. L., & Klimchuk, J. A. 2023, *ApJ*, 944, 158),

We performed a wide variety of community service. As indicated above, we lead the ISWAT team and developed software tools and techniques for community use. Other activities included training students and post-docs, organizing sessions at conferences, serving on committees, supporting mission development, etc. Details can be found in our May presentation to the external review committee. An important service that should not be overlooked is the role we play as science leaders, guiding the direction of international coronal heating research.

### 3. Papers

(submitted and/or accepted during fiscal year 2023)

1. "Heating and Cooling in Stellar Coronae: Coronal Rain on a Young Sun", Daley-Yates, S, Jardine, M. M. and Johnston, C. D. 2023, MNRAS, 526, 1646
2. "The Transition Region of Solar Flare Loops," Gontikakis, C., Antiochos, S. K. & Young, P. R., 2023, ApJ, 943, 120, doi: 10.3847/1538-4357/aca8a9
3. "Observational Signatures of Coronal Heating in Magnetohydrodynamic Simulations without Radiation or a Lower Atmosphere," Klimchuk, J. A., Knizhnik, K. J., & Uritsky, V. M. 2023, ApJ, 942, 10, doi: 10.3847/1538-4357/ac9f41
4. "The Thickness of Current Sheets and Implications for Coronal Heating," Klimchuk, J. A., Leake, J. E., Daldorff, L. K. S., & Johnston, C. D. 2023, Front. Phys., 11, 1198194, doi: 10.3389/fphy.2023.1198194
5. "Modeling of Condensations in Coronal Loops Produced by Impulsive Heating with Variable Frequencies and Locations," Kucera, T. A., Klimchuk, J. A., & Luna, M. 2023, ApJ, submitted
6. "Role of Small-Scale Impulsive Events in Heating the X-ray Bright Points of the Quiet Sun," Mondal, B., Klimchuk, J. A., et al. 2023, ApJ, 945, 37, doi: 10.3847/1538-4357/acb8bb
7. "Reconnection-generated Plasma Flows in the Quasi-separatrix Layer in Localized Solar Corona", Mondal S., Srivastava A.K., Mishra S.K., Sangal K., Kayshap P., Guo Y., Pontin D.I., Uritsky V.M., Ofman L., Wang T., Yuan D., ApJ, 2023, 953, 84, doi: 10.3847/1538-4357/acd2da
8. "Data-constrained Solar Modeling with GX Simulator," Nita, G. M., Schonfeld, S., Klimchuk, J. A., et al. 2023, ApJ Supp, 267, 6, doi: 10.3847/1538-4365/acd343
9. "Center-to-Limb Variation of Transition Region Doppler Shift in Active Regions," Rajhans, A., Tripathi, A., Kashyap, V. L., & Klimchuk, J. A. 2023, ApJ, 944, 158, doi: 10.3847-4357/acb4ed
10. "Progress and Challenges in Understanding the Ambient Solar Magnetic Field, Heating, and Spectral Irradiance," Reiss, M. A., Arge, C. N., Henney, C. J., Klimchuk, J. A., Schonfeld, S., et al. 2023, Advances in Space Research, in press, doi: 10.1016/j.asr.2023.08.039
11. "Self-similar Outflows at the Source of the Fast Solar Wind: A Smoking Gun of Multiscale Impulsive Reconnection?", Uritsky V.M., Karpen J.T., Raouafi N.E., Kumar P., DeVore

C.R., DeForest C. E., ApJL, 2023 955, L38, doi: 10.3847/2041-8213/acf85c

12. "Are Coronal Loops Projection Effects?" Uritsky, V. M. & Klimchuk, J. A. 2023, ApJ, submitted

#### 4. Presentations

(only those with team members as first author; many other presentations are not included)

1. "Nonthermal Velocities and Other Properties of a Quiescent Active Region Observed by EUNIS and EIS: Implications for Coronal Heating," Brosius, J. W., Daw, A. N., Rabin, D. M., Landi, E., & Schmit, D. (AGU Fall Meeting; Chicago; 12/14/22)
2. "Nonthermal Velocities and Other Properties of a Quiescent Active Region Observed by EUNIS and EIS: Implications for Coronal Heating," Brosius, J. W., Daw, A. N., Rabin, D. M., Landi, E., & Schmit, D. (SPD Meeting; Minneapolis; 8/15/23)
3. "The CubeSat Imaging X-ray Spectrometer (CubIXSS)," Caspi, A., Klimchuk, J. A. et al. (SPD meeting; Minneapolis; 8/15/23)
4. "Diagnosing Loops with Varying Cross-Sectional Area using Emission Measure", Chhabra, S., Reep, J., Knizhnik, K., Klimchuk, J.A. (SPD meeting; Minneapolis; 08/18/23)
5. "Implication of Line Tied Magnetic Field on Magnetic Reconnection in the Closed Corona," Daldorff, L. K. S., Leake, J. E., & Klimchuk, J. A. (AGU meeting; Chicago; 12/15/22)
6. "Implication of Line-Tied Magnetic Field on Magnetic Reconnection in the Closed Corona," Daldorff, L. K. S., Leake, J. E., & Klimchuk, J. A. (Magnetic Reconnection 2023 meeting; Ise-Shima, Japan; 6/28/23)
7. "Implication of Line Tied Magnetic Field on Magnetic Reconnection in the Closed Corona," Daldorff, L. K. S., Leake, J. E., Klimchuk, J. A., & Johnston, C. D. (SPD meeting; Minneapolis; 8/17/23)
8. "Implication of Line Tied Magnetic Field on Magnetic Reconnection in the Closed Corona," Daldorff, L. K. S., Leake, J. E., Klimchuk, J. A., & Johnston, C. D. (LWS team meeting; APL, Laurel, MD; 9/28/23)

9. "Transition Region Adaptive Conduction (TRAC) Method: Comparing DEMs from MHD Simulations of Impulsive Heating & TNE", Johnston, C. D., Barnes, W. T., Daldorff, L. K. S., & Daley-Yates, S. (ISSI Team Meeting; Bern, Switzerland; 3/13/23)
10. "Self-Consistent Heating of the Magnetically Closed Corona: Generation of Nanoflares and Response of the Plasma," Johnston, C. D., Daldorff, L. K. S., Klimchuk, J. A., Sow Mondal, S., & Leake, J. E. (SPD meeting; Minneapolis; 8/16/23)
11. "The Role of 3D Complexity in Magnetic Reconnection," Klimchuk, J. A., Daldorff, L. K. S., Leake, J. E. (LWS team meeting; Huntsville, AL; Oct. 12, 2022)
12. "Magnetospheric Nanoflares?," Klimchuk, J. A. (LWS team meeting; Huntsville, AL; Oct. 14, 2022)
13. "Coronal Heating: Globally and Within Campfires," Klimchuk, J. A. (Solar Orbiter "Atmospheric Heating" Science Working Group; Oct. 17, 2022)
14. "The Role of 3D Complexity in Magnetic Reconnection," Klimchuk, J. A., Daldorff, L. K. S., & Leake, J. E. (AGU meeting; Chicago; Dec. 12, 2022)
15. "Cross Sections of Coronal Loop Flux Tubes," Klimchuk, J. A., DeForest, Craig. E. (GSFC Poster Party; Jan. 26, 2023)
16. "The Difference Between Thermal Non-equilibrium and Thermal Instability," Klimchuk, J. A. (ISSI Team Meeting; Bern, Switzerland; Mar. 13, 2023)
17. "Condensation Formation with Nanoflare Heating," Klimchuk, J. A., Kucera, T. A., & Luna, M. (ISSI Team Meeting; Bern, Switzerland; Mar. 16, 2023)
18. "The Unavoidable Thinning of Current Sheets," Klimchuk, J. A. (work package team meeting; Apr. 5, 2023)
19. "The Heating of the Magnetically Closed Corona," Klimchuk, J. A., Johnston, C. D. (ISFM mid-term review; GSFC; 5/16/23)
20. "The Thickness of Electric Current Sheets and Implications for Coronal Heating," Klimchuk, J. A. (STAMP meeting; GSFC; 6/2/23)
21. "Why is the Corona So Darned Hot?," Klimchuk, J. A. (GSFC interns; 6/15/23)
22. "The Thickness of Electric Current Sheets and Implications for Coronal Heating," Klimchuk, J. A., Leake, J., E., Daldorff, L. K. S., & Johnston, C. D. (Magnetic Reconnection 2023 meeting; Ise-Shima, Japan; 6/26/23)

23. "The Thickness of Current Sheets and Implications for Coronal Heating," Klimchuk, J. A., Leake, J., E., Daldorff, L. K. S., & Johnston, C. D. (ISFM work package team meeting; 7/26/23)
24. "The Thickness of Current Sheets and Implications for Coronal Heating," Klimchuk, J. A., Leake, J., E., Daldorff, L. K. S., & Johnston, C. D. (SPD meeting; Minneapolis; 8/17/23)
25. "Advice to Students and Early-Career Scientists," Klimchuk, J. A. (SPD meeting; Minneapolis; 8/17/23)
26. "Modeling the Solar Spectral Irradiance Using GX\_Simulator," Klimchuk, J. A. (ISFM work package team meeting; 9/6/23)
27. "Loss of Equilibrium in Current Sheets: A Pathway to Reconnection Onset," Klimchuk, J. A. (LWS team meeting; APL, Laurel, MD; 9/26/23)
28. "Modeling of Condensations in Coronal Loops Produced by Impulsive Heating with Variable Frequencies and Locations," Kucera, T. A., Klimchuk, J. A., & Luna, M. (SPD meeting; Minneapolis; 8/17/23)
29. "The Onset of Magnetic Reconnection in Dynamically Evolving Current Sheets in the Solar Corona," Leake, J. E., Daldorff, L. K. S., & Klimchuk, J. A. (Magnetic Reconnection 2023 meeting; Ise-Shima, Japan; 6/28/23)
30. "The Onset of Magnetic Reconnection in Dynamically Evolving Current Sheets in the Solar Corona," Leake, J., E., Daldorff, L. K. S., & Klimchuk, J. A. (SPD meeting; Minneapolis; 8/17/23)
31. "The Onset of Magnetic Reconnection in Dynamically Evolving Coronal Current Sheets," Leake, J., E., Daldorff, L. K. S., & Klimchuk, J. A. (LWS team meeting; APL, Laurel, MD; 9/28/23)
32. "The Effect of Cross-Section Expansion on the Evolution of Coronal Loops," Lopez Fuentes, M., Klimchuk, J. A. (XVII Latin American Regional IAU; Montevideo, Uruguay; Nov. 27-Dec. 1, 2023)
33. "On the Role of Spicules in Solar Coronal Emission," Sow Mondal, S., Klimchuk, J. A., & Sarkar, A. (SPD meeting; Minneapolis; 8/17/23)