Heating of the Magnetically Closed Corona

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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 8 research papers submitted and/or accepted[1] and the 37 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 current sheets,

[1] Additional papers published during the period but accepted previously are not included in the total.

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

A fundamental question concerns the onset of magnetic reconnection. Reconnection must remain dormant as magnetic stresses slowly build and then suddenly turn on to release a burst of energy. If onset happens too soon, there is not enough stress and stored magnetic energy to explain explosive phenomena like CMEs, flares, coronal jets, etc. More importantly for our purposes, nanoflares and the associated coronal heating are weak.

We have made an exciting theoretical discovery concerning reconnection onset. Depending on the level of magnetic shear in a current sheet (shear refers to the rotation of the magnetic field vector across the sheet), an equilibrium may or may not be possible. In a slowly driven system like the corona, where complex photospheric motions twist and tangle the multitude of magnetic strands, magnetic shear slowly increases. We propose that current sheets reach a critical shear, whereupon they spontaneously collapse and immediately reconnect. We derived an approximate formula for the critical shear (Klimchuk et al. 2023), and we have recently performed rigorous MHD simulations to verify that the formula is accurate (Kee et al.). This work represents a major breakthrough.

We have also investigated another possible pathway to reconnection onset. Reconnection begins with the tearing instability. Photospheric driving decreases the thickness of current sheets at the same time that it increases the shear. The tearing mode growth rate increases as sheets become thinner. In a fat sheet where the growth rate is slower than the thinning rate, the instability is effectively nonexistent. But when the sheet becomes thin enough that the growth rate and thinning rate are comparable, the instability takes off and the sheet rapidly reconnects. We published a recent paper on this idea (Leake, Daldorff, & Klimchuk 2024). Whether current sheet thinning or current sheet loss of equilibrium is more common on the Sun is something we plan to investigate.

Finally, we completed our study of the effect of line-tying on magnetic reconnection. This refers to the fact that coronal field lines are rigidly rooted in the photosphere. Line-tying can inhibit or even prevent reconnection depending on the length of the field line (coronal strand). A final revision to the paper is being made now (Daldorff, Leake, & Klimchuk 2024).

Multi-Strand Simulations

We have made major advances in this area as well. After a substantial development time, our LaRe3D MHD simulation setup is ready for modeling the complex physics of interacting magnetic strands in a realistic solar atmosphere extending from the photosphere, through the chromosphere and transition region, and into the corona. This will be our workhorse moving forward. The realism of the simulations is amazing, and the synthetic images made from them are exquisite. We are already obtaining valuable new insights. We have confirmed with far more rigor than our earlier study with a different code that bright coronal loops correspond to storms of nanoflares (Johnston et al.), and we have measured the energy distribution and occurrence frequency of nanoflares (Sow Mondal et al.). The results were presented at several meetings, and papers are being prepared.

Whole Active Region Models

We model entire active regions using of the GX Simulator tool, which we helped develop. We constructed preliminary models of a particular active region and varied the assumed nanoflare properties to determine which provide the best agreement with observations (Kucera et al.).

As stated above, our long-range goal is to develop physics-based models of active regions and the solar spectral irradiance (SSI), which is dominated by active regions in many wavebands of space weather importance. We created the International Space Weather Action Team (ISWAT) S2-06 on Physical Origins of the Solar Spectral Irradiance, co-led by Klimchuk and Chhabra, to involve entire international community in this crucial activity. During the reporting period, we convened the first meeting of the team. It was held at the Applied Physics Lab of Johns Hopkins University and was a great success by all accounts. We devised an action plan of modeling activities that team members will undertake before our next meeting, scheduled for summer 2025 in Oslo, Norway. Models will be compared with each other and with a variety of solar observations. After much consideration, a particular active region was selected for this purpose (Kucera et al.).

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. Our paper was accepted and published during the reporting period (Kucera, Klimchuk, & Luna 2024).

We measured nonthermal velocities in active regions (Brosius 2024). We modeled mass flows that result from impulsive heating in expanding loops (Reep, Chhabra, et al. 2024), likely the source of the observed nonthermal broadening. We investigated the cross section of a coronal loop observed from two vantage points and found that the implied approximately circular shape is consistent with the predictions of our multi-strand simulations (Mandal, Klimchuk, et al. 2023). We studied coronal rain on another star (Daley-Yates, Jardine, & Johnston 2023). And we developed an improved method of modeling thermal conduction, which a fundamentally important process in our multi-strand simulations (Caplan, Johnston, Daldorff, & Linker 2024).

We performed a wide variety of community service. As indicated above, we led 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. 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 the period)

1. “Nonthermal Velocities in a Solar Active Region Observed by SERTS,” Brosius, J. W, ApJ, submitted

2. “Advancing parabolic operators in thermodynamic MHD models II: Evaluating a Practical Time Step Limit for Unconditionally Stable Methods”, Caplan, R. M., Johnston, C. D., Daldorff, L. K. S. and Linker, J. A. 2024, Journal of Physics: Conference Series, 2742, 012020.

3. “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

4. “The Thermodynamic Response of Heating at Coronal Null Points”, Johnson, D., Hood, A. W., Cargill, P. J., Reid, J. and Johnston, C. D. 2024, MNRAS, 532, 4261

5. “Modeling of Condensations in Coronal Loops Produced by Impulsive Heating with Variable Frequencies and Locations,” Kucera, T. A., Klimchuk, J. A., & Luna, M. 2024, ApJ, 965, 53

6. “The Onset of Magnetic Reconnection in Dynamically Evolving Coronal Current Sheets,” Leake, J. E., Daldorff, L. K. S., & Klimchuk, J. A. 2024, ApJ, 973, 21

7. “Investigating Coronal Loop Morphology and Dynamics from Two Vantage Points,” Mandal, S., Peter, H., Klimchuk, J. A., et al. 2023, AA, 682, L9

8. “Mass Flows in Expanding Coronal Loops”, Reep, J.W., Scott, R.B., Chhabra, S., Unverferth, J., & Knizhnik, K.J., 2024 ApJ 967, 53

4. Presentations

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

1. "Nonthermal Velocities in a Quiescent Solar Active Region Observed by EUNIS and EIS," J. W. Brosius, A. N. Daw, D. M. Rabin, E. Landi, & D. Schmit (AGU Fall Meeting; San Francisco; 12/13/2023)

2. "The CubeSat Imaging X-ray Solar Spectrometer (CubIXSS): A New Mission to Understand Heating of Coronal Plasma," A. Caspi, J. A. Klimchuk, A. Shih, et al. (AGU Fall Meeting; San Francisco; 12/12/23)

3. "The CubeSat Imaging X-ray Solar Spectrometer (CubIXSS): Science and Current Status of Implementation for a New Mission to Understand Heating of Coronal Plasma," A. Caspi, J. A. Klimchuk, et al. (TESS 2024; Dallas; 4/12/24)

4. "Diagnosing Loop Expansion in Active Regions using Emission Measure," S. Chhabra, J. W. Reep, K. Knizhnik, & J. A. Klimchuk (TESS 2024; Dallas; 4/12/24)

5. "Diagnosing Loop-Expansion in Active Regions Using Emission Measure," S. Chhabra, J. Reep, K. Knizhnik, & J. A. Klimchuk (11th Coronal Loops Workshop; La Laguna, Canary Islands; 6/26/24)

6. "Implication of Line Tied Magnetic Field on Magnetic Reconnection in the Closed Corona," L. K. S. Daldorff, J. E. Leake, J. A. Klimchuk, & C. D. Johnston (AGU Fall Meeting; San Francisco; 12/13/23)

7. "Implication of Line Tied Magnetic Field on Magnetic Reconnection in the Closed Corona," L. K. S., Daldorff, J. E. Leake, J. A. Klimchuk, & C. D. Johnston (SpiroFest; Boulder; 2/29/24)

8. Implication of Line-Tied Magnetic Field on Magnetic Reconnection in the Closed Corona," L. K. S., Daldorff, J. E. Leake, & J. A. Klimchuk (TESS 2024; Dallas; 4/12/24)

9. "Range of Scales in Active Regions and Their Influence on Energy Release," L. K. S. Daldorff, C. D. Johnston, S. Sow Mondal, J. A. Klimchuk, J. E. Leake, & N. D. Kee (11th Coronal Loops Workshop; La Laguna, Canary Islands; 6/26/24)

10. "Does the Coronal Heating Rate Depend on Microscopic Reconnection Physics?", Y.-M. Huang & A. Bhattacharjee (SHINE Workshop; Juneau, Alaska; 8/12/24)

11. "Self-Consistent Heating of the Magnetically Closed Corona: Generation of Nanoflares and Response of the Plasma," C. D. Johnston, L.K.S. Daldorff, J. A. Klimchuk, J. E. Leake, & S. Sow Mondal (AGU Fall Meeting; San Francisco; 12/12/23)

12. "Self-Consistent Heating of the Magnetically Closed Corona: Generation of Nanoflares and Response of the Plasma," C. D. Johnston, L. K. S. Daldorff, J. A. Klimchuk, S. Sow Mondal, & J. E. Leake (11th Coronal Loops Workshop; La Laguna, Canary Islands; 6/26/24)

13. "Self-Consistent Heating of the Magnetically Closed Corona: Generation of Nanoflares and Response of the Plasma," C. D. Johnston, L. K. S. Daldorff, J. A. Klimchuk, J. E. Leake, & S. Sow Mondal (TESS 2024; Dallas; 4/10/24)

14. "LaRe3D Modeling 2," C. D. Johnston, J. E. Leake, J. A. Klimchuk, L. K. S. Daldorff, & S. Sow Mondal (1st Meeting of ISWAT Team S2-6; APL/JHU, 7/29/24)

15. "The Thickness of Current Sheets and Implications for Coronal Heating," J. A. Klimchuk, J. E. Leake, L. K. S. Daldorff, & C. D. Johnston (AGU Fall Meeting; San Francisco; 12/12/23)

16. "The Onset of Magnetic Reconnection in Thinning Current Sheets," J. A. Klimchuk, J. E. Leake, L. K. S. Daldorff, C. D. Johnston, & S. Sow Mondal (AGU Fall Meeting; San Francisco; 12/15/23)

17. "Thermal Non-Equilibrium: As Fascinating and Important as Spiro Himself," J. A. Klimchuk, T. A. Kucera, & M. Luna (SpiroFest; Boulder; 3/1/24)

18. "Loss of Current Sheet Equilibrium as a Pathway to Reconnection Onset," J. A. Klimchuk, N. D. Kee, & J. E. Leake (TESS 2024; Dallas; 4/12/24)

19. "Thermal Non-Equilibrium: As Fascinating as it is Important," J. A. Klimchuk (Coronal Cooling Conference; Leuven; 5/21/2024; invited)

20. "Loss of Current Sheet Equilibrium: the Nanoflare Trigger?", J. A. Klimchuk, N. Dylan Kee, & J. E. Leake (11th Coronal Loops Workshop; La Laguna, Canary Islands; 6/26/24)

21. "Meeting Introduction and LaRe3D-hydro-GXsimulator Modeling Overview," J. A. Klimchuk (1st Meeting of ISWAT Team S2-6; APL/JHU, 7/29/24)

22. "Physical Models of Solar Active Regions and the Solar Spectral Irradiance," J. A. Klimchuk, C. D. Johnston, & S. Chhabra (Director's Seminar; GSFC; 9/18/24; invited)

23. "Modeling of Condensations in Coronal Loops Produced by Impulsive Heating with Variable Frequencies and Locations," Therese Kucera, James Klimchuk, and Manuel Luna (11th Coronal Loops Workshop; La Laguna, Canary Islands; 6/25-28/24)

24. "The Onset of Magnetic Reconnection in the Solar Corona," J. E. Leake, L. K. S. Daldorff, J. A. Klimchuk, & C. D. Johnston (TESS 2024; Dallas; 4/12/24)

25. "LaRe3D Modeling 1," J. E. Leake, C. D. Johnston, J. A. Klimchuk, L. K. S. Daldorff, & S. Sow Mondal (1st Meeting of ISWAT Team S2-6; APL/JHU, 7/29/24)

26. "The role of modeling and observations for a complete explanation of coronal heating," Lopez Fuentes, M. (XVII Latin American Regional IAU Meeting; Montevideo, Uruguay; 11/27/23; invited)

27. "The effect of cross-section expansion on the evolution of coronal loops," Lopez Fuentes, M. & Klimchuk, J. A. (XVII Latin American Regional IAU Meeting; Montevideo, Uruguay; 11/29/23)

28. "Hydrodynamic modeling of coronal loops," M. Lopez Fuentes & J. A. Klimchuk (66th Meeting of the Argentinian Aston. Assoc.; La Plata, Argentina; 9/16/24)

29. "Stereoscopic Analysis of Coronal Loop Morphology and Dynamics," S. Mandal, J. A. Klimchuk, et al. (11th Coronal Loops Workshop; La Laguna, Canary Islands; 6/25/24)

30. "Temporal and spatial evolution of nanoflare heating in solar AR," B. Mondal, J. A. Klimchuk, A.R. Winebarger, P.S. Athiray, J. Liu; (11 th Coronal Loops Workshop; La Laguna, Canary Islands; 6/26/24)

31. "Long-Lived Active Regions: Identification and Heating Implications," E. I. Mason, K. Kniezewski, C. Downs, N. M. Viall, W. T. Barnes, J. A. Klimchuk, & A. R. Winebarger (TESS 2024; Dallas; 4/10/24)

32. "The Coronal Microscale Observatory," D. Rabin, J. A. Klimchuk, et al. (TESS 2024; Dallas; 4/10/24)

33. "Advancements in Understanding the Ambient Solar Magnetic Field, Heating, and Spectral Irradiance: A Roadmap Update from COSPAR ISWAT Cluster S2," M. Reiss, C. N. Arge, J. Klimchuk, et al. (45th COSPAR Scientific Assembly; Busan, Korea, 7/13/24)

34. "Nanoflare Statistics in a Driven Magnetically Closed Corona," S. Sow Mondal, L.K.S. Daldorff, J. A. Klimchuk, C. D. Johnston, & J. E. Leake (AGU Fall Meeting; San Francisco; 12/12/23)

35. "Nanoflare Statistics and Reconnection Onset in the Magnetically Closed Corona," S. Sow Mondal, L. K. S. Daldorff, J. A. Klimchuk, C. D. Johnston, & J. E. Leake (TESS 2024; Dallas; 4/12/24)

36. "Nanoflare Frequency and Reconnection Onset in Driven Active Region Magnetic Fields," S. Sow Mondal, C. D. Johnston, L. K. S. Daldorff, J. A. Klimchuk, J. E. Leake, & N. D. Kee (11th Coronal Loops Workshop; La Laguna, Canary Islands; 6/26/24)

37. "Nanoflare Statistics," S. Sow Mondal, L. K. S. Daldorff, J. A. Klimchuk (671), & C. D. Johnston (1st Meeting of ISWAT Team S2-6; APL/JHU, 7/30/24)