Physical Models of Solar Active Regions and the Solar Spectral Irradiance

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We propose a strategic, forward leaning, and well-defined project to address a problem of great importance to NASA and the nation. At the start of the ISFM program, we laid out a comprehensive long-range plan to study coronal heating as a prerequisite for modeling the solar spectral irradiance (SSI). We have been highly successful, as evidenced by our outstanding reviews and mid-term evaluations. The physical understanding and numerical capabilities developed in the first two ISFM cycles have prepared us for a big payoff now. In partnership with colleagues at NASA's Marshall Space Flight Center (Marshall) and Ames Research Center (Ames), **we will build the most realistic physical models of solar active regions ever achieved.**

Active regions are very bright and dominate the SSI at wavelengths most important for space weather. Extreme ultraviolet (EUV) and X-ray radiations are important inputs to the terrestrial upper atmosphere. Intermediate timescale (one to several day) variability associated with active region evolution and rotation onto and off the visible solar disk has major space weather impacts [1,2,3,4]. Variations in thermospheric heating change the drag experienced by orbiting objects and complicate collision avoidance operations. Variations in the background state of the ionosphere affect the occurrence of ionospheric bubbles that cause scintillation of radio signals and disrupt communication and navigation systems. Modifications of the electron density altitude profile alter radio ray paths and impact over-the-horizon radar. Substantial improvements in operational space weather nowcasting and forecasting will require a major advance in modeling the SSI. The existing empirical models have an important role for the time being, but just as with tropospheric weather forecasting, empirical models must ultimately be superseded by physical models. We will develop these models.

The spectral irradiance of active regions is also very important for other stars and their planetary systems. It impacts the photochemistry, heating, and escape of exoplanet atmospheres [5,6]. Furthermore, UV radiation plays an important role in the origin and development of life [7]. To characterize and understand exoplanet atmospheres requires knowledge of the radiative inputs, but such knowledge is inadequate for important wavebands. We will develop physical models of stellar active regions to provide the crucial missing information.

Active regions have tremendous complexity on small spatial scales. The magnetic field is subdivided into an enormous number of quasi-independent flux strands – of order 10^5 in a single active region [8]. The coronal strands become twisted and tangled by complex photospheric convective flows in which they are rooted at their base. Electric current sheets form at the strand boundaries. Magnetic stresses steadily build until critical conditions are met, and explosive reconnection releases a burst of energy that heats the plasma. This is the famous nanoflare. Each nanoflare is too small to be detected individually – though mission concepts are being developed to one day do so – but collectively they heat the corona to its multi-million degree temperatures.

Our current ISFM team has made tremendous progress in understanding nanoflare reconnection, including the fundamental property of reconnection onset [9,10,11], which has major implications for phenomena throughout the universe. However, this is just one part of the story. To model the spectrum of emitted radiation, we must understand how plasma responds to the heating. This involves a thin, crucially important layer at the base of the corona called the transition region (TR). Mass and energy are exchanged freely between the corona and TR via thermal conduction and flows along field lines. In fact, roughly half of the energy released in the corona is radiated from the TR rather than directly from the corona itself. This is obviously important for the SSI and must be included in any meaningful model.

Existing MHD simulations of active regions do not include the small-scale complexity of the magnetic field, and many do not properly treat the TR. The number of numerical grid cells required to capture the 10^5 current sheets is prohibitive, and resolving the thin TR across an entire active region is an extreme challenge. Consequently, the heating mechanism in the simulations is different from that on the real Sun. It typically involves artificially large Ohmic dissipation of large-scale currents, which is much more passive than the explosive reconnection of nanoflares.

Methodology

We propose a **new and highly innovative approach** that includes all the important effects. It involves three elements. We begin with state-of-the-art MHD simulations using the LaRe3D code [12], but instead of treating a whole active region in one simulation, we simulate only a small portion of the magnetic flux, extending from one photospheric footpoint to the other. We call these **multi-strand MHD simulations** (element 1) because they limit the number of strands and current sheets to a resolvable quantity but include enough that collective behavior can occur.

Figure 1 is an example of one of our simulations. Outlined on the Hi-C rocket image of panel (a) is a volume comparable to that of the simulation, shown in (b). The field has been straightened (large-scale curvature effects are not important) and a sine wave has been used for gravity, so that a photosphere, chromosphere, and TR are present at both the top and bottom, representing opposite polarity parts of the active region. The colored surfaces in (b) are iso-contours of current density showing the sheets that separate the strands. Panel (c) shows the emissivity (radiation per unit volume per unit time) in a mid-plane cut across the field, as it would be detected in the 211 Å channel of AIA/SDO (T~2 MK). Panel (d) is a simulated 211 Å image for a view from the side. The simulation uses our TRAC technique for accurately capturing the physics of the TR with far fewer grid cells than are normally required [13]. It also uses our novel approach of placing the layer of imposed photospheric driving well inside the computational domain, to avoid spurious boundary condition effects that plague some other simulations. An additional advantage is the use of compressive viscosity, which allows us to follow the flow of reconnection energy as it occurs on the Sun – from magnetic, to kinetic, to thermal.

We will run many simulations with different field strengths B and strand lengths L. The goal is to build a library of models that sample all the conditions expected throughout an active region. With such a library we can construct models of any active region by assembling the

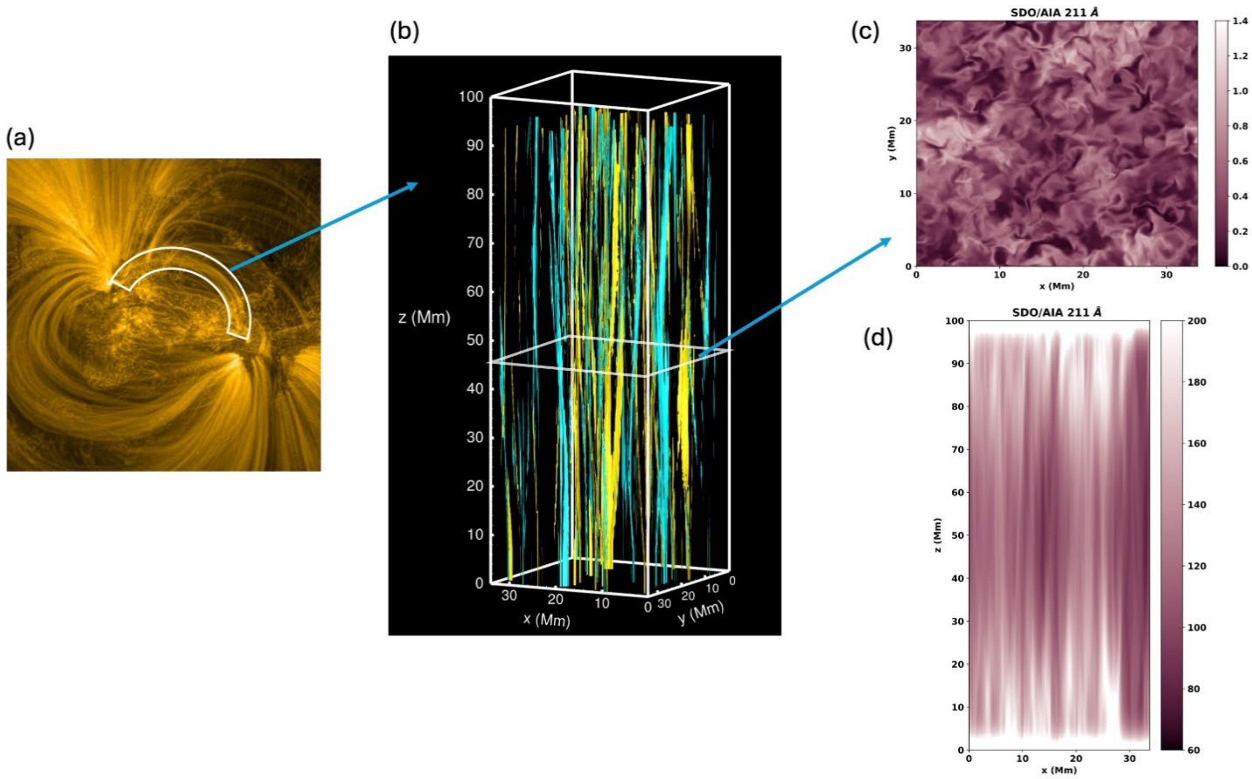

Figure 1. Example multi-strand MHD simulation. (a) Hi-C 193 Å rocket image of an active region. (b) Iso-contours of vertical current density (blue, yellow for J_z positive, negative). (c) Emissivity (erg cm^{-3} s^{-1}) as would be detected in the 211 Å channel of SDO/AIA in a cross-field cut through the mid-plane. (c) Simulated 211 Å image for view from the side. Simulations like this will be used to build a library of models for constructing entire active regions based on observed photospheric magnetograms.

appropriate pieces, as described below. However, because the multi-strand simulations are computationally intensive, the initial library is likely to be rather sparse. In the interim, therefore, we will make use of far quicker field-aligned hydrodynamic simulations. We will analyze the MHD multi-strand results to determine how the heating properties (energy and frequency distributions of nanoflares) depend on B and L. We will then use those dependencies to run a very large number of **EBTEL hydro simulations** (element 2) with assumed nanoflare inputs. EBTEL is a fast and easy-to-use code we developed that is now a workhorse of the solar community [14,15,16]. It can be used to model both the corona and TR.

Rapidly evolving small-scale structures are the fundamental building blocks of the corona, yet each individual brightness fluctuation contributes only a tiny fraction to the spectral irradiance. Even observationally distinct loops make relatively minor contributions to active region emission, which is dominated by a diffuse component [17,18]. To model the spectral irradiance, we need be concerned only with gradual changes that occur over the roughly half day evolutionary timescale of active regions. The precise timing of individual (stochastic) loop brightenings is unimportant. We will therefore populate our model library using the time-averaged output from the simulations. The library entries will contain the time-averaged differential emission measure, $\mathrm{DEM}(T)$, as a function of B and L. We can compute the intensity that would be observed by any instrument by convolving DEM(T) with the instrument response function or spectral line contribution function.

The final element of our approach employs the **GXsimulator active region modeling tool** (element 3), which we helped develop [19,20]. GXsimulator starts with an observed photospheric magnetogram and constructs a nonlinear force-free coronal magnetic field. An example is shown in Figure 2a. It then fills the volume with plasma on a voxel-by-voxel basis. Each voxel (3D pixel) is assigned a DEM(T) from the model library based on the B and L of the field line passing through its center. Images are then created by integrating along lines of sight. Figure 2b shows a synthetic AIA 211 Å image for an assumed nanoflare distribution. Panel (c) shows the actual image for comparison. Note that the synthetic image represents a time average, while the actual image does not. We will validate our models with time-averaged data as discussed below. Also note that no attempt was made to adjust the assumed nanoflare properties to achieve better agreement. GXsimulator is capable of generating radio images, which are sensitive to the magnetic field as well as the plasma and therefore offer an additional test of the model.

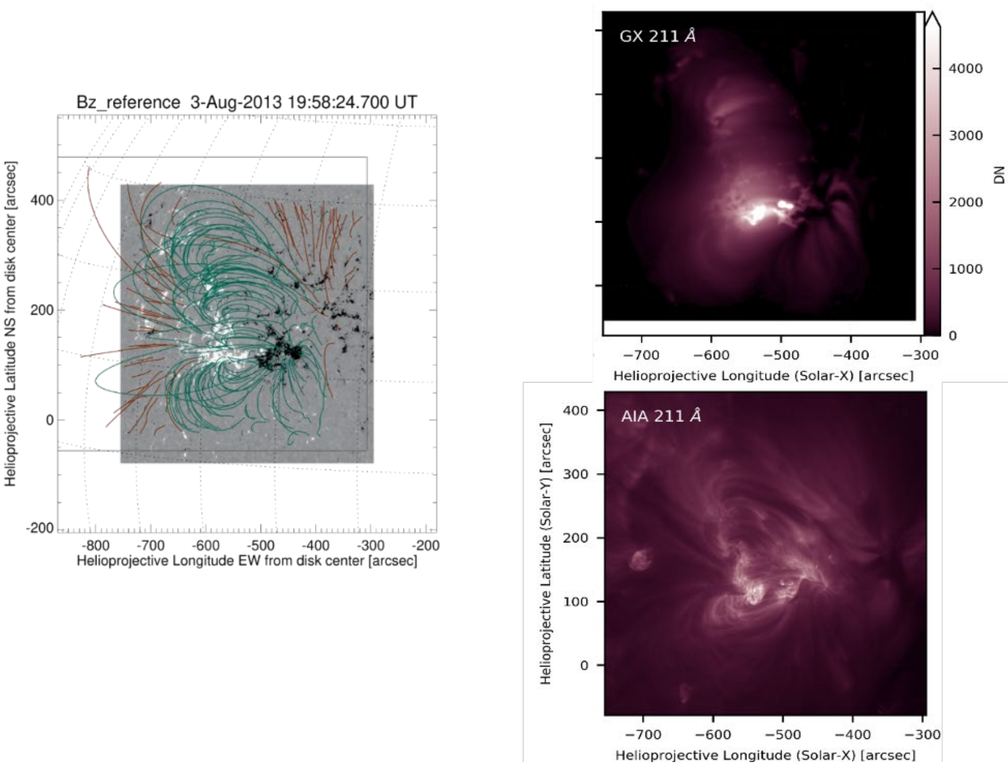

Figure 2. Example GXsimulator model of an active region. (a) Observed photospheric magnetogram and extrapolated magnetic field. (b) Synthetic SDO/AIA 211 Å image. (c) Actual 211 Å image.

A major advantage of our unique approach is that, once the library of multi-strand/EBTEL models is created, it is straightforward to construct any observed active region. GXsimulator runs quickly, which is crucial for space weather operations. A model is of limited operational value if it takes many days to run, as is the case for other approaches.

Model Improvements

We plan improvements to our multi-strand simulations before embarking on the production runs. The multi-strand nature of the corona arises for three reasons: (1) magnetic flux is concentrated in clumps in the photosphere, (2) complex photospheric driving shears, rotates, and otherwise distorts the flux; and (3) coronal reconnection modifies the topological connections. Our present simulations only include the second and third effects. We will improve the simulations by incorporating realistic nonuniform flux distributions and by imposing more realistic driver flows. These improvements will be based on our state-of-the-art **magnetoconvection simulations** using the radiative MHD StellarBox code [21,22] and the latest high-resolution observations from the Daniel K. Innoye Solar Telescope (DKIST). Figure 3 is an example magnetogram and velocity vector map from a StellarBox quiet Sun simulation. We will perform new simulations with conditions appropriate to active regions. We will then quantitatively analyze the output to determine the important characteristics of the magnetic and velocity fields. We will use several complementary data analysis techniques, including anisotropic power spectral analysis [23] and higher-order structure functions [24], which will allow us to identify the variability of the velocity and vorticity field across a range of spatial and temporal scales. Finally, we will implement a data-constrained spectral representation method [25] to generate synthetic magnetic and velocity fields with these same characteristics. These will be used to initialize and drive our multi-strand simulations. If capabilities become available in the future, we may drive the simulations with data assimilated directly from StellarBox. We will validate the StellarBox results – and adjust the multi-strand inputs as necessary – using high-resolution observations from DKIST. Our technique for measuring the in-place rotation of observed magnetic elements will be especially useful for identifying vortex flows that twist coronal strands [26].

The concentrated magnetic fields in the high-β photosphere flare out rapidly with height to become space filling in the low-β corona. This may affect the preferred location of nanoflare reconnection, which opens the possibility of thermal non-equilibrium (TNE) – a phenomenon we have studied in great detail [27,28]. If it turns out that TNE is common, we may need to use hydro codes like ARGOS [29] and HYDRAD [30] instead of EBTEL to populate our library of models. This would be computationally more intensive but is not prohibitive. The expansion of the magnetic field also affects the relative proportion of radiation coming from the corona and transition region. This modifies the shape of the irradiance spectrum, which is important for space weather because different wavelengths are absorbed at different altitudes in the terrestrial atmosphere. Our recent improvements to EBTEL now allow for flux tube expansion [16].

We will explore high frequency driving and associated wave heating in our models. We note, however, the general view that wave heating – while dominant in coronal holes and possibly important in the quiet Sun – is small compared to reconnection heating in active regions [31,32,33].

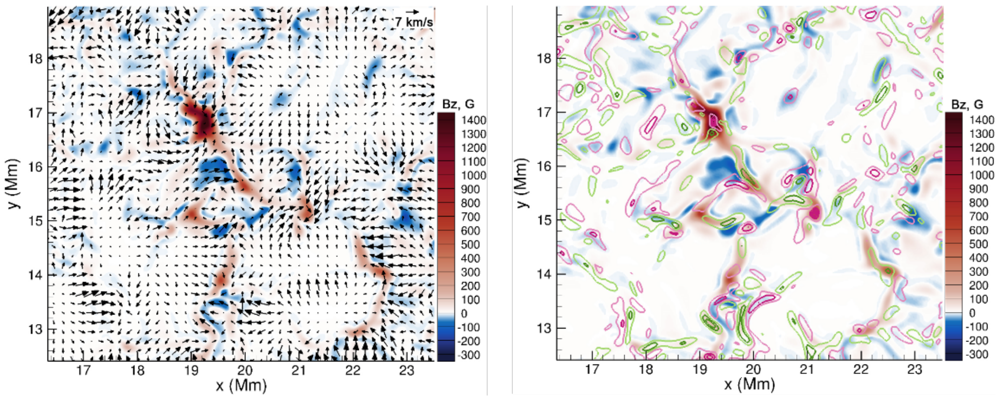

Figure 3. Example magnetoconvection simulation from StellarBox. (left) Vertical magnetic field in color and horizontal velocity vectors. (right) Vertical magnetic field and contours of + and - vertical vorticity (curl V_{hor}). Such simulations will be used to determine important characteristics of the magnetic and velocity fields that will be used to initialize and drive our improved multi-strand simulations.

Model Validation

We will rigorously test our active region models with observations. We will make quantitative comparisons with spatially resolved images from SDO/AIA, Hinode/XRT, the MaGIXS rocket, the Expanded Owens Valley Solar Array (EOVSA), and from MUSE and CubIXSS once they are launched. We will use time-averaged observations to match our time-averaged simulations. If successful, our models will show similar spatial variations across the active region to what is seen in the data.

We will also test our models with spectral irradiance observations from SDO/EVE [34]. We will isolate active region emission in the full disk SSI data by searching for days when only one active region was present and subtracting the SSI from a day when there were no active regions. Figure 4 is a spectrum obtained in this way.

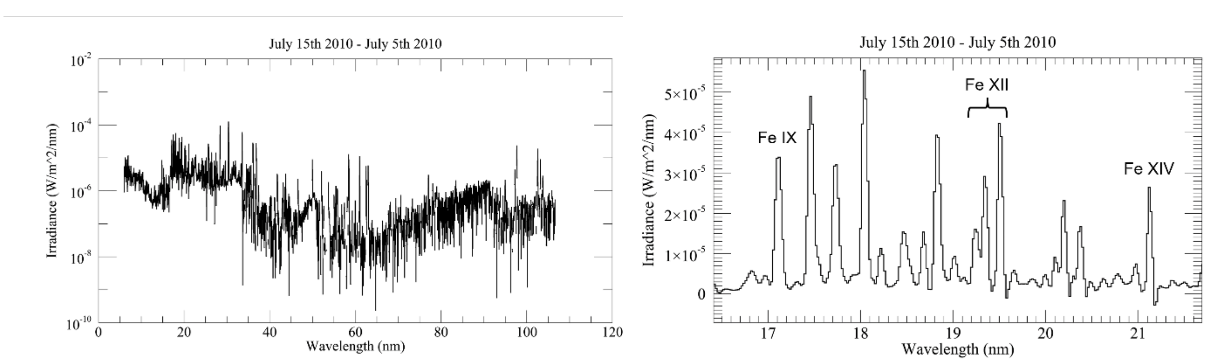

Figure 4. (left) Full SDO/EVE irradiance spectrum of a single active region obtained by subtracting the full-disk SSI of a day without any active regions from a day with only one active region. (right) Close up of the spectrum showing the lines for which the SDO/AIA 171, 193, and 211 Å channels were named. Spectra like these will be used to evaluate our active region models.

We will directly evaluate our multi-strand simulations by comparing them with high-spatial resolution observations (not time averaged) from Solar Orbiter/EUI, the Hi-C rocket, and (when launched) VISORS. The ability to produce distinguishable loops is an important test of the physics in the model, even if the loops do not, by themselves, have a big influence on the irradiance. Our simulations suggest that loops represent storms of nanoflares. They appear as clusters of emissivity in cross-field cuts like Figure 1c [35]. The storms seem to represent an avalanche-like process, which we plan to explore further. This explanation of loops is in sharp contrast to the veil hypothesis [36], which is based on a whole active region simulation without small-scale strands. Observations favor the nanoflare storm scenario [37,38].

We will also test our active region models and individual multi-strand simulations with spectroscopic observations from Hinode/EIS, IRIS, SolO/SPICE, and the EUNIS rocket. Diagnostics will include Doppler shifts and nonthermal line broadening [39], $\mathrm{DEM}(T)$ slopes [40,41,42], and time lags [43,44].

We will model stellar active regions in the same way we model solar active regions, using the best available information on their sizes and field strengths and the velocities and spatial scales of the convective driving. These parameters vary for stars with different rotation rates, etc.

Distinct ISFM Effort

Our proposed work builds upon but is clearly distinct from our current ISFM effort. We have made great strides in unraveling fundamental properties of individual magnetic reconnection events occurring in isolated, idealized geometries, as well as understanding how the plasma responds to impulsive heating within individual magnetic strands. Now it is time to advance to the realm of ensembles of strands with realistic geometries. The numerical tools necessary for breakthrough progress are finally at a stage where this is possible, and preliminary results indicate that fascinating collective behavior is at play. Leveraging our earlier success, we will develop the most advanced physical models of active regions and their spectral irradiance ever achieved.

Personnel and Management

This highly ambitious project requires a concerted effort of many scientists with a wide range of expertise working together over an extended period. It is far beyond the scope of the HSR program. Goddard, augmented by our colleagues at Marshall and Ames, is the only organization in the world with the necessary combination of theorists, modelers, and observers. Success requires a sustained, long-term effort. The ultimate product – highly realistic physical models of active regions – requires a level of stability that is not possible with small research grants.

We have found it highly beneficial to have a majority of team members collocated – yet another reason why this project is ideally suited to a center. Regular in-person interactions, both planned and impromptu, have proved extremely valuable to our current team. We will continue our successful tradition of full team meetings every other week, with sub-groups meeting regularly on a weekly basis.

Our team retains many members of our current team and adds new members to fill gaps in expertise. We have both funded CoIs and unfunded Collaborators. Though the Collaborators will not receive direct support from this ISFM project, they have other sources of funding to support their contributions. All our main objectives can be accomplished by CoIs alone. The Collaborators will enhance the effort, largely in an advisory or supplemental role. We will likely expand the team with unofficial members, as has happened with our current team. People learn about the exciting work we are doing and ask to be involved. Their participation has been mutually beneficial, allowing us to accomplish more than originally planned. This open approach gives us a stronger and more wide-reaching connection with the community, which is a valuable form of service.

An appendix lists the members of the team and their specific roles. We here emphasize the exciting partnership we are forming with our sister NASA centers. CoI Irina Kitiashvili at Ames will perform the magnetoconvection simulations. CoI Adam Kobelski and Collaborator Biswajit Mondal at Marshall will run EBTEL and GXsimulator and perform observational comparisons with data from the Marshall Hi-C and MaGIXS rocket experiments and other sources such as CubIXSS.

We are also excited about the new collaboration we have started with Allison Youngblood and Sarah Peacock of Goddard's Astrophysics Division (667). They will provide guidance for our stellar active region models and be our interface with the Astrophysics community. We will also strengthen our connections with other labs within Goddard's Heliophysics Division. Joshua Pettit of the ITM Lab (675) and Yihua Zheng of the Space Weather Lab (674) will provide guidance on space weather aspects, and Joshua will study the correlation between the SSI and ionospheric scintillation.

Our team is very diverse in both gender and age.

Community and National Benefit

Our project will benefit the science community and the nation in multiple ways. Most obviously, the SSI is an important driver of space weather, adversely affecting collision avoidance activities and any systems that involve the propagation of electromagnetic signals (communication, navigation, over-the-horizon radar, etc.). The ability to nowcast and eventually forecast the SSI is of great importance to our national security and economic well-being. Empirical models are the best we can do at present, but significantly improved capabilities will require a physics-based approach. This was exactly the case with tropospheric weather forecasting, progressing from simple empirical models to sophisticated atmospheric simulations. Jonah Colman, Space Environment Mission Lead at the Air Force Research Lab, has strongly endorsed our effort. He states that anything impacting the environment where electromagnetic signals propagate is critically important, and that developing physics-based models of the SSI would be highly worthwhile (private communication). Recently, the Heliophysics Division at NASA HQ officially elevated the importance of orbital debris and space situational awareness (OD-SSA). It is now included in the definition of the Space Working Environment, and a joint MOU was signed in support of R&D for Space Traffic Management and Neutral Density Modeling.

This problem is so important that it demands an international response. For this reason, we have formed an International Space Weather Action Team (ISWAT S2-06) under the auspices of COSPAR called Origins of the Spectral Irradiance and its Intermediate Timescale Variability. It is concerned with SSI variations on timescales of one to several days related to active region evolution and rotation, and so is closely aligned with our ISFM proposal. The team has over 55 members. It is described in [45], and more information can be found at our website: https://iswat-cospar.org/S2-06. The first team meeting will be held July 29-31, 2024 at the Applied Physics Lab of Johns Hopkins University (https://secwww.jhuapl.edu/EventLink/Event/395). As discussed earlier, ours is not the only approach to modeling active regions, though we believe it is the best because it is the only one to include the multi-stranded nature of the corona. The main purpose of the ISWAT team is to compare and contrast the different approaches and determine which best reproduces observations, especially of the spectral irradiance.

Our revolutionary multi-strand simulations are the motivation for future NASA missions. They are the foundation of the science case for the Coronal Microscale Observatory (CMO) concept proposed to the Decadal Survey and SHARPI MidEx concept currently being pursued at Goddard. These are both ultra-high-resolution missions to investigate the exquisite small-scale structures evident in the simulated image of Figure 1d. Up to now the existence of nanoflares has been inferred based on spatially integrated emission from many events. These will be the first observations to capture individual nanoflares.

Nanoflares are the only heating mechanism capable of producing plasma hotter than 5 MK, but the high-temperature emission is expected to be very faint. Future missions that target this emission – such as the FIERCE concept proposed to the Decadal Survey and now being studied as a MidEx and the MaGIXS concept also being studied as a MidEx – need predictions of the brightness of the emission. Instrument design studies for all these missions will rely on our simulations to determine requirements for spatial resolution, sensitivity, and spectral coverage (emission lines and band passes matched to expected temperatures).

Studies of exoplanet atmospheres require knowledge of stellar active regions, as discussed earlier. Future mission concepts devoted to this topic will also benefit from our efforts. These include ESCAPE, SNOUT, and UV-SCOPE.

We will share openly with the community any new advances we make on numerical techniques, as we have done in the past. During the current ISFM cycle, we led or contributed significantly to improvements in LaRe3D, EBTEL, and GXsimulator. All three of these codes are being widely used by the community. Among the improvements are the TRAC method for treating the TR [13], the addition of cross-sectional area variations [16] and kinetic energy [46] in EBTEL, and the addition of non-homogenous nanoflare distributions in GXsimulator [20].

We will make our LaRe3D-based multi-strand simulation code available to the community so it can be used by others in their research. We will release a version including routines for thermal conduction and TRAC on the https://git.smce.nasa.gov NASA gitlab under a https://ti.arc.nasa.gov/opensource/nosa/} NOSA license or https://github.com/Warwick-Plasma/Lare3d/blob/main/LICENSE Apache License Version 2.0. Our published results will include the LaRe3D release version, startup files, and appropriate metadata to enable reproducibility.

We will provide our ultimate product – the combined simulation library and active region modeling tool – to the Community Coordinated Modeling Center (CCMC) so that active region model outputs can be provided to the community on demand. Such outputs could include images, spectral irradiance, and physical variables such as differential emission measure distributions. We envision that a version of our tool will ultimately be used for routine space weather operations.

The ISWAT team is just one example of how our leadership benefits the science community. Other examples of organizational leadership include serving on scientific organization committees (SOC) for conferences and as organizers of individual sessions. We have a long history of this type of service and will continue. PI James Klimchuk started the Triennial Earth-Sun Summits (TESS) and the highly successful Coronal Loops Workshop series, now in its 22nd Year. CoI Craig Johnston currently serves on the Steering Committee and SOC of "Loops" and wrote a successful proposal to obtain funding for students to attend this year's meeting.

We feel a strong responsibility to train the next generation of Heliophysicists. During the current ISFM cycle, we have co-advised the PhD research of graduate students, mentored summer interns, and trained post-docs. Our proposing team includes a graduate student, Gabriela Gonzalez, and two post-docs within 2 years of their degree, Shanwlee Sow Mondal and Biswajit Mondal. We will look to add more as opportunities arise.

We also play an important unofficial leadership role. We are very active in discussions at conferences and are frequently sought out for guidance, often resulting in fruitful collaborations. As mentioned above, our visibility and leadership in the community has inspired many people to join our team as unofficial members.

In summary, we propose a strategic, forward-leaning program to build the most realistic physical models of solar and stellar active regions and their spectral irradiance ever achieved. This ambitious effort requires a large team with diverse skills that has stable funding over an extended period. Our team establishes an exciting new partnership among the Goddard and Marshall Space Flight Centers and the Ames Research Center. It forges a new collaboration between the Heliophysics and Astrophysics Divisions at Goddard and strengthens ties among different labs within the Heliophysics Division. Our efforts will benefit the broader community in multiple ways, including the development of new research tools, most notably the multi-strand MHD simulation code and the active region modeling tool, which we will share with the community and CCMC. Our results will be used to define the observing requirements of missions currently under study. Our leadership of the ISWAT team will for the first time coordinate the disjoint efforts of different international research groups to produce a major advance in active region studies. We will provide additional leadership by organizing meetings and meeting sessions and by training the next generation of scientists. Finally, we will benefit the nation by creating the forerunner of the first physics-based operational model of the solar spectral irradiance.

References

1. Kopp, G., & Shapiro, A. 2021, Sol. Phys., 296, 60
2. Vourlidas, A. & Bruinsma S. 2018, Space Weather, 16, 5
3. Schmolter, E., Verdermann, JBerdermann, J., Jakowski, N., Jacobi, C.,& Vaishnav, R. 2018, Adv. Radio Sci., 16, 149
4. Lilensten, J., Dudok de Wit, T., Kretzschmar, M., et al. 2008, Ann. Geophys., 26, 269
5. Peacock, S., Barman, T., Shkolnik, E. L., et al. 2019, ApJ, 886, 77
6. Teal, D. J., Kempton, E. M. R., Bastelberger, S., Youngblood, A., & Arney, G. 2022, ApJ, 927, 90
7. Airapetian, V. S., Barnes, R., Cohen, O., et al. 2019, Int. Journal Astrobiology, 19, 136
8. Klimchuk, J. A. 2015, Phil. Trans. R. Soc. A, 373, 20140256
9. Leake, J. E., Daldorff, L. K. S., & Klimchuk, J. A. 2020, ApJ, 891, 62
10. Klimchuk, J. A., Leake, J. E., Daldorff, L. K. S., & Johnston, C. D. 2023, Front. Phys., 11, 1198194
11. Leake, J. E., Daldorff, L. K. S., & Klimchuk, J. A. 2024, ApJ, submitted
12. Arber, T. D., Longbottom, A. W., Gerrard, C. L., & Milne, A. M. 2001, JCoPh, 171, 151
13. Johnston, C. D., et al. 2020, AA, 635, A168
14. Klimchuk, J. A., Patsourakos, S., & Cargill, P. A. 2008, ApJ, 682, 1351
15. Cargill, P. J., Bradshaw, S. J., & Klimchuk, J. A. 2012, ApJ, 752, 161
16. Cargill, P. J., Bradshaw, S. J., Klimchuk, J. A., & Barnes, W. T. 2022, MNRAS, 509, 4420
17. Viall, N. M., & Klimchuk, J. A. 2011, ApJ, 738, 24
18. Del Zanna, G., & Mason, H. E. 2003, AA, 406, 1089
19. Nita, G. M., Viall, N. M., Klimchuk, J. A., et al. 2018, ApJ, 853, 66
20. Nita, G. M., Fleishman, G. D., Kuznetsov, A. A. , et al. 2023, ApJ Supp, 267, 6
21. Wray, A. A., Bensassi, K., Kitiashvili, I. N., Mansour, N. N., & Kosovichev, A. G. 2015, arXiv: 1507.07999
22. Wray, A. A., Bensassi, K., Kitiashvili, I. N., Mansour, N. N., & Kosovichev, A. G. 2018, in Variability of the Sun and Sun-Like Stars: from Asteroseismology to Space Weather, ed. J. P. Rozelot & E. S. Babayev (Les Ulis: EDP Sciences), 39
23. Knizhnik, K., Uritsky, V., Klimchuk, J., & DeVore, C. R. 2018, ApJ, 853, 82
24. Uritsky, V., Roberts, M., Karpen, J., & DeVore, C. R. 2017, ApJ 83, 123
25. Wang, Y., Azam, A., Wilson, M., et al., 2021, Proc. Institution of Mechanical Engineers, Part J, 235:12, 2640
26. Van Kooten, S. J. & Cranmer, S. R. 2024, ApJ, 964, 50
27. Klimchuk, J. A. & Luna, M. 2019, ApJ, 884, 68
28. Kucera, T. A., Klimchuk, J. A., & Luna, M. 2024, ApJ, 965, 53
29. Antiochos, S. K., MacNeice, P. J., Spicer, D. S., & Klimchuk, J. A. 1999, ApJ, 512, 985

30. Bradshaw, S. J. & Cargill, P. J. 2010, ApJ, 717, 163
31. Van Doorsselaere, T., Srivastava, A. K., Antolin, P. et al. 2020, SSR, 216, 140
32. Viall, N. M., De Moortel, I., Downs, C., Klimchuk, J. A., Parenti, S., & Reale, F. 2021, in Space Physics and Aeronomy Collection Vol. 1: At the Doorstep of Our Star: Solar Physics and Solar Wind, Geophys. Monograph 258, eds: N. E. Raoufi & A. Vourlidas) (AGU; Wiley)
33. Howson, T. A., De Moortel, I., & Fyfe, L. E. 2020, A&A, 643, A85
34. Woods , T. N., Eparvier, F. G., Hock, R., et al. 2012, Solar Phys, 275, 115
35. Klimchuk, J. A., Knizhnik, K. J., & Uritsky, V. M. 2023, ApJ, 942, 10
36. Malanushenko, A., Cheung, M. C. M., DeForest, C. E., Klimchuk, J. A., & Rempel, M. 2022, ApJ, 927, 1
37. Klimchuk, J. A., & DeForest, C. E. 2020, ApJ, 900, 167
38. Uritsky, V. M. & Klimchuk, J. A. 2024, ApJ, 961, 222
39. Lopez Fuentes, M., & Klimchuk, J. A. 2022, ApJ, 939, 17
40. Winebarger, A. R., Schmelz, J. T., Warren, H. P., et al. 2011, ApJ, 740, 2
41. Warren, H. P., Winebarger, A. R., & Brooks, D. H. 2012, 759, 141
42. Bradshaw, S. J., & Viall, N. M. 2016, ApJ, 821, 63
43. Viall, N. M., & Klimchuk, J. A. 2012, ApJ, 753, 35
44. Winebarger, A. R., Lionello, R., Downs, C., et al. 2016, ApJ, 831, 172
45. Reiss, M. A., Arge, C. N., Henney, C. J., Klimchuk, J. A., et al. 2023, Advances in Space Research, in press, doi: 10.1016/j.asr.2023.08.039
46. Rajhans, A., Tripathi, D., Bradshaw, S. J., Kashyap, V. L., & Klimchuk, J. A. 2022, ApJ, 924, 13

Narrative of Tasks

High level milestones and measures of success are discussed throughout the main text of the proposal, and we here present a list of specific tasks (detailed milestones) for each year, followed by a description of which team members will work on them.

Year 1

A. Improve multi-strand simulations to include nonuniform photospheric magnetic flux distribution and large-scale field expansion; determine influence on spatial and temporal properties of heating.
B. Begin to compare multi-strand simulations with observations (loop widths and lifetimes, DEM distributions, time lags, Doppler shifts, etc.).
C. Provide mission and instrument development teams with observing requirements (spatial and temporal resolution, spectral channels, etc.).
D. Perform magnetoconvection simulations with active region conditions; begin to analyze to determine fundamental spatial and temporal characteristics of photospheric field and flows.
E. Perform EBTEL hydro simulations with different assumed nanoflare energy and frequency (occurrence rate) distributions; assemble library of models for input to GXsimulator.
F. Construct GXsimulator models of active regions using model library and assumed parameterized heating (power-law dependence on B, L, etc.); begin to compare with imaging observations of active regions to determine best-fit nanoflare frequencies and heating parameters.
G. Begin to analyze DKIST observations to determine fundamental spatial and temporal characteristics of photospheric field and flows; compare with magnetoconvection simulations.
H. Begin to isolate active region spectral irradiance from SDO/EVE whole Sun spectral irradiance (SSI) observations.
I. Collect information on stellar active regions (size, field strength, convective flows, etc.).
J. Begin to study correlation between ionospheric scintillation and SSI.
K. Coordinate efforts of ISWAT team; organize second team meeting depending on cadence decided by team.
L. Organize sessions at conferences.
M. Expand involvement of students and early career scientists, especially from under-represented groups.
N. Publish research papers.
O. Serve on review panels.

Year 2

A. Continue comparison of multi-strand simulations with observations, especially new datasets that may become available.
B. Continue comparison of GXsimulator models with observations.

C. Complete analyses of magnetoconvection simulations and DKIST observations; use derived characteristics to generate highly realistic initial conditions and driver flows for new multi-strand simulations.
D. Investigate high frequency driving (wave generation) and assess impact on heating; incorporate into models as basic feature if found to be important (not anticipated).
E. Perform improved multi-strand simulations with realistic initial conditions and driving; assemble (relatively sparce) library of simulations to be used to determine "actual" coronal heating parameters and nanoflare distributions.
F. Compare improved multi-strand simulations with observations.
G. Run multi-strand and EBTEL simulations of stellar active regions; begin to build GXsimulator models of stellar active regions.
H. Complete observational study of active region spectral irradiance.
I. Complete study of correlation between scintillation and SSI.
J. Continue to coordinate activities of ISWAT team; organize second or third team meeting depending on cadence.
K. Continue to organize sessions at conferences.
L. Continue to expand involvement of students and early-career scientists.
M. Continue to publish research papers.
N. Continue to serve on review panels.

Year 3

A. Assemble dense library of EBTEL simulations based on "actual" coronal heating parameters and nanoflare distributions determined from sparce library of multi-strand simulations.
B. Build GXsimulator models of active regions based on EBTEL model library; compare and contrast active regions of differing size and complexity.
C. Compare active region models with imaging observations and results from spectral irradiance study.
D. Compare multi-strand simulations with any new observations that become available.
E. Continue to populate multi-strand simulation library to eventually supersede EBTEL library.
F. Compute the spectral irradiance of model stellar active regions and assess the impact on planetary atmospheres and the development of life; provide observing parameter guidance to developers of astrophysics missions and instruments.
G. Make the multi-strand simulation tool (LaRe3D together with setup and driving modules) available to the research community.
H. Provide the active region modeling tool (GSsimulator and integrated library of models) to CCMC.
I. Continue to coordinate activities of ISWAT team and organize team meeting depending on cadence.
J. Continue to organize sessions at conferences.
K. Continue to expand involvement of students and early-career scientists.
L. Continue to publish research papers.
M. Continue to serve on review panels.

Team Member Responsibilities

Note that all the primary goals can be accomplished by funded CoIs alone.

PI James Klimchuk (GSFC Solar Lab) will oversee the project and ensure coordination among the different interconnected tasks. He will be actively and directly involved in most of the tasks, especially those involving simulation and modeling. He leads the ISWAT team.

Deputy PI Therese Kucera (GSFC Solar Lab) will assist with the overall coordination. She will run GXsimulator models and compare them with imaging and spectroscopic observations, especially those from SDO/AIA, Hinode/EIS, IRIS, SolO/SPICE.

CoI Irina Kitiashvili (ARC) will perform and analyze magnetoconvection simulations.

CoI Adam Kobelski (MSFC) will perform EBTEL simulations, run GXsimulator models, and make observational comparisons with data from the Marshall Hi-C and MaGIXS rocket experiments and other sources such as CubIXSS.

CoIs James Leake (GSFC Solar Lab), Craig Johnston (GSFC/GMU), Shanwlee Sow Mondal (GSFC/CUA), and Lars Daldorff (GSFC/CUA) will improve the multi-strand simulations, assemble the simulation library, analyze the results to obtain insights about coronal heating – including nanoflare distributions and parameterizations for the EBTEL simulations – and assist in the comparison with observations. They will make our codes and software developments assessable by the community.

CoI Sherry Chhabra (NRL/GMU) will run GXsimulator models and compare with observations, especially radio observations from EOVSA. She co-leads the ISWAT team.

CoI Vadim Uritsky (GSFC/CUA) will analyze magnetic and velocity fields from magnetoconvection simulations and DKIST observations to determine characteristic properties.

Collaborator Biswajit Mondal (MSFC) will perform EBTEL simulations, run GXsimulator models, and make observational comparisons with data from the Marshall Hi-C and MaGIXS rocket experiments and other sources such as CubIXSS.

Collaborators Allison Youngblood and Sarah Peacock (GSFC Astrophysics Division) will provide guidance on the stellar active region models and assess their planetary atmosphere and origin of life impacts. They will interact with the Astrophysics community and provide input for mission and instrument development.

Collaborators Gabriela Gonzalez (student, U. Colorado) and Philip Chamberlin (LASP) will analyze spectral irradiance observations to isolate the active region component and compare with GXsimulator models.

Collaborator Joshua Pettit (GSFC ITM Lab) will provide guidance on space weather impacts and study the correlation between ionospheric scintillation and SSI.

Collaborator Yihua Zheng (GSFC Space Weather Lab) will provide guidance on space weather impacts and oversee the installation of the active region modeling tool to the CCMC collection.

Collaborator Samuel Van Kooten (SWRI) will make DKIST observations of magnetic and velocity fields in the photosphere for comparison with magnetoconvection simulations and to initialize and drive multi-strand simulations.