Heating of the Magnetically Closed Corona

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1. Executive Summary

We propose 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. Specifically, we will 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. Using a combination of numerical simulations, theory, and observations, we will investigate the many physical effects and the highly disparate and coupled spatial scales that are involved. Magnetic reconnection – a fundamental process – is at the heart of the problem, and by understanding nanoflares, we will gain insights into many other heliophysical and astrophysical phenomena. Furthermore, coronal heating powers the X-ray and UV radiation that controls the terrestrial upper atmosphere, and our work will lay the foundation for improved predictions of the solar spectral irradiance and its space weather impacts. This effort is ideally suited for a work package because of the complex and multi-faceted nature of the problem. Our Goddard team is unique in having the full range of backgrounds and skills necessary to be successful. By supporting the community through scientific advances and leadership, training the next generation, organizing meetings, developing numerical tools, and assisting instrument and mission planning, we will usher in a new era of understanding and progress.

2. Science Relevance, Goals, and Objectives

Explaining why the solar corona is 2-3 orders of magnitude hotter than the underlying solar surface – the famous coronal-heating problem – remains one of the great challenges of space science [1,2,3,4]. To understand many phenomena, including those of space weather importance, we must solve this long-standing mystery. It is important to distinguish between the magnetically closed corona, where field lines are rooted to the surface at both ends, and the magnetically open corona, where one end extends far out to space. The process of heating may be fundamentally different in these two environments. Coronal holes and the solar wind are almost certainly heated by waves, likely involving turbulence, and Parker Solar Probe should reveal many of the missing details [5,6]. Our research program instead concerns magnetically closed active regions and "quiet" Sun. They are also subjected to wave heating, but small magnetic reconnection events are thought to be even more important [4]. These regions are responsible for the vast majority of UV and X-ray emission from the Sun and are the source of coronal mass ejections and flares. They may also provide the mass for the slow solar wind, which escapes via reconnection with adjacent open field lines [7,8].

The energy for the heating originates in the complex motions of the massive photosphere. Turbulent convection slowly displaces the footpoints of coronal field lines, causing them to become twisted and tangled. Magnetic stresses gradually build until reaching a breaking point, whereupon a sudden burst of energy is released. This basic picture of "nanoflares" has been widely accepted since advocated long ago by Parker [9], but many fundamental aspects have remained out of reach. Challenges include an enormous range of physically coupled spatial scales and confusion associated with spatial and temporal averaging inherent in optically thin observations. Only a multi-pronged approach involving observation, theory, and simulation can produce a breakthrough. This requires a sizable, co-located team and is ideally suited for a work package.

Stated in simple terms, the goal of our proposed effort is to **determine when, where, and why nanoflares occur, and how the impulsively heated plasma responds to produce the inhomogeneous thermal structure of the corona**. Underlying this goal are many specific objectives. We will examine nanoflare properties such as their magnitude, recurrence frequency, and height distribution. We will determine how these properties depend on physical parameters such as magnetic field strength and field-line length, and therefore how they vary within and among active regions, and between active regions and the quiet Sun. We will investigate how nanoflares behave collectively to produce observational features such as coronal loops. We will also determine the relationship between nanoflares and the important phenomenon of thermal nonequilibrium [10].

The physical connection between the corona and lower atmosphere involves more than the driving of magnetic footpoints and stressing of the field. Another coupling involves processes such as field-aligned thermal conduction and flows, including chromospheric evaporation. These crucial aspects of the plasma response control the evolving temperature and density, which determine the brightness and spectrum of emitted radiation. It is imperative to take them into account when testing theoretical models with observations. Furthermore, the solar spectral irradiance in the UV and X-ray is an important driver of space weather in the ionosphere-thermosphere-mesosphere (ITM) and magnetosphere system here at Earth [11]. Effects such as drag, scintillation, and changing electron-density height profiles impact collision avoidance, communication, navigation, and precision weapons guidance [12]. A major motivation of our research is to **provide the physical understanding necessary to develop improved operational models for predicting solar spectral irradiance variability on timescales of one to several days**. Such variability is associated with the evolution of active regions and rotation of active regions onto and off the visible disk. As described below, one of our modeling efforts for investigating the physics could ultimately be transitioned to an operational model.

The physics of coronal heating is not unique to the Sun. The spectral irradiance of other stars affects conditions in their planetary systems and likely plays a crucial role in the development of life [13]. Magnetic reconnection, the process responsible for nanoflares, is fundamental to many phenomena throughout the universe, such as black hole accretion disks [14] and gamma-ray bursts [15]. On the Sun, reconnection is responsible for CMEs, flares, and jets, in addition to coronal heating. Closer to home, it controls the buildup and release of the magnetic energy that drives geomagnetic substorms. Flux transfer events on the dayside [16] and bursty bulk flows in the magnetotail [17] indicate localized reconnection events reminiscent of nanoflares. Thus, the insights gained from our work package effort will have **widespread applicability and advance the understanding of many heliophysical and astrophysical phenomena**. Our program is closely aligned with Science Mission Directorate objectives. It directly addresses two of the top-level goals of the Decadal Survey for Heliophysics: Goal 1. Determine the origins of the Sun's activity and predict the variations in the space environment, and Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe. The heating of the magnetically closed corona is a primary motivation for many past, present, and planned missions, including SDO, Hinode, IRIS, Solar Orbiter, EUVST/Solar-C, and MUSE.

The proposed research is, to a large degree, a continuation of our current work package, which was always intended to be a long-term effort. We have been very productive. All our formal and informal evaluations from program managers, as well as input from unaffiliated colleagues, have been extremely positive. Following their encouragement, we will continue on this successful path, making adjustments according to the new knowledge we have gained.

3. Methodology Including Data, Theory, and Models

As noted, a major challenge in studying coronal heating is the extreme range of spatial scales involved. The clumpy nature of the photospheric magnetic field, combined with the complexity of the driving, results in a corona that is subdivided into elemental flux tubes, or strands, whose characteristic size is ~100 km [3,18]. The strands are misaligned and therefore separated by even thinner (~1 km) current sheets. This is where nanoflare reconnection occurs. The driving flows are themselves mesoscale (~1000 km), as are coronal loops, which are bundles of multiple strands that appear to be heated by transient “storms” of closely spaced nanoflares. Lastly, nanoflare properties such as their magnitude vary strongly over the large scales (~10,000 km) of an active region. All these scales must be taken into account to avoid spurious conclusions and to obtain a comprehensive understanding of coronal heating. Unfortunately, it is not possible to treat the full range in a single do-it-all numerical simulation. There are more than 10^5 current sheets in a single active region [3], and several 10s of grid points are needed across each sheet to adequately resolve the initial reconnection dynamics. Our strategy is to **investigate each of these spatial scales separately, in great detail, and use the insights gained from one investigation to inform the design and interpretation of other investigations, at all times being cognizant of how the different scales are linked**. Close coordination is key, which is a major advantage of having co-located team members.

We will use a variety of closely integrated approaches. State-of-the-art **numerical simulations** are at the core of our research plan. **Observations** will be used heavily to motivate the simulations and evaluate their realism. **Analytical theory** will be used to validate the simulations and develop physical insights. Only a team with expertise in all these areas can be fully successful, and we have assembled just such a team. To our knowledge, Goddard is the only place in the world that can make such a claim, at least in the context of coronal heating.

We next discuss our research plan in greater detail, starting with our investigation of small spatial scales and progressing to meso and large scales.

3.1 Onset of Magnetic Reconnection (Small Scale)

A fundamental aspect of reconnection is its switch-on property. The reconnection must remain at low levels to allow magnetic stresses to build substantially. If it were to become efficient too soon, the stresses would be small and the corresponding energy release would be weak. The corona would be much cooler than observed, and CMEs, flares, and jets would be much less energetic. What are the physical onset conditions for fast reconnection and what is their explanation? We have made a recent breakthrough in answering these crucial questions [19].

It is widely agreed that reconnection begins with the tearing instability of current sheets [20]. The instability involves many modes, each associated with a familiar chain of magnetic islands, which are the cross sections of flux tubes lined up side-by-side. Modes of different wavelength are present at the same time, and there are many more modes, with a variety of orientations, in the presence of a guide field [21]. This is the situation for coronal heating, where the guide field is generally stronger than the reconnecting field component. The tearing modes grow independently at first, but once they become nonlinear, they begin to interact in complex ways. Using sophisticated numerical simulations, we have developed a conceptual framework that organizes the many rather confusing results in the reconnection literature. Whether and how fast reconnection develops depends in a predictable way on the relative linear growth rates of the modes. What is especially exciting is that these growth rates depend on the current-sheet properties (width, length, shear angle) and can be easily determined from linear theory. Thus, we have identified the physical onset conditions of fast reconnection. Our results are only preliminary, however, because our modeled current sheets are very idealized. We propose a series of additional simulations with increasing realism to place our new understanding on a much firmer footing.

Current sheets become progressively thinner as the stresses in the magnetic field increase. The tearing instability transitions from being very slow to very fast. Under coronal conditions, this occurs when sheets are far wider than kinetic scales, so an MHD treatment is appropriate. After rigorously testing several codes, we settled on LaRe3D [22], a state-of-the-art 3D MHD code that has been used successfully on many problems. Unlike most competitors, it includes explicit shock viscosity to treat the flow of energy as it actually occurs on the Sun: from magnetic, to kinetic, to thermal. We have verified that the linear growth rates of the many tearing modes are accurately reproduced [21]. Should circumstances arise in which the treatment of kinetic effects is important, we have considerable experience with particle-in-cell and embedded-PIC codes [23].

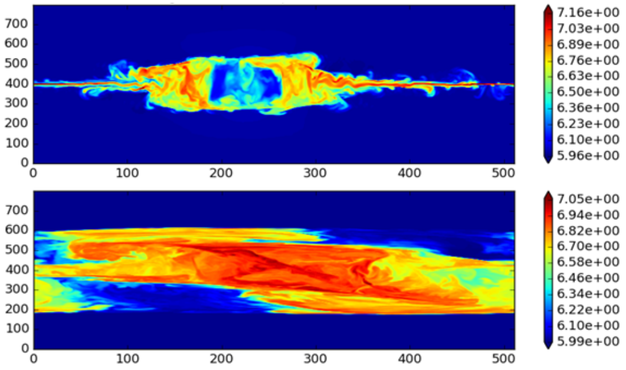

Figure 1: Temperature maps (log T) for long (top) and short (bottom) current sheets with large shear (spatial units are grid number in the nonuniform grid).

Our initial study used triply periodic boundary conditions and a nonuniform grid to fully resolve a single 3D current sheet. We considered undriven force-free equilibrium sheets of different length and shear angle (rotation of the field across the sheet). Figure 1 shows temperature in planes cutting through two of the sheets. Thermal conduction and radiation were not included in these runs, so the actual temperatures would be less than the 10 MK indicated. These examples reveal that, for a given shear (40° half angle), long and short sheets exhibit dramatically different behavior. A large plasmoid/island, formed from the coalescence of smaller plasmoids, dominates in the long sheet, whereas a band of complex turbulence develops in the short sheet (see also [24,25]). In still other cases, the current sheet is minimally disrupted, and little energy is released.

By studying undriven current sheets like these, we can identify the conditions required for fast reconnection. However, to truly address reconnection onset, we must simulate sheets that are slowly evolving in the manner expected from footpoint driving. We will first consider the effect of slow thinning at fixed shear by increasing the gas pressure far from the sheet. We will next consider the effect of slow shearing, using line-tied conditions at the "photospheric" boundaries. Because line-tying is potentially important even without driving – for example, by inhibiting the coalescence of islands, which is one of the evolutionary paths to fast reconnection – we will perform line-tied simulations both with and without imposed footpoint driving. We have successfully executed preliminary runs to confirm that these approaches are sound.

The next big step in realism will be to investigate current sheets of finite length. Periodic boundary conditions introduce a limiting length scale by setting the wavelength of the longest tearing mode allowed in the system, which we have shown to be extremely important. Other effects are missing, however, such as the expulsion of reconnected field out the ends of the sheet [26]. This is potentially important for reconnection onset, and it will certainly affect the subsequent evolution, including how long the reconnection is sustained and how small scales couple to larger scales. We will therefor study current sheets that terminate at magnetic Y-points at both ends. Equilibrium configurations of this type exist for infinitely thin sheets [27]. However, after considering the force balance both across and along the sheet, we have tentatively concluded that equilibrium sheets cannot have both finite length and finite width. Flows and low-level reconnection must be occurring. We will investigate these effects and how they influence the onset of fast reconnection and explosive energy release. One approach is to study the collapse of an X-point into a current sheet with double Y-points. Another is to broaden an infinitely thin sheet using temporarily large resistivity. We will investigate both.

As discussed above, the path to fast reconnection can involve the development of turbulence or the formation and coalescence of plasmoids/flux ropes. We would like to distinguish between these possibilities with observations. Nanoflare current sheets are far too small to be seen in images, so we must rely instead on spectroscopy. We have begun to generate synthetic line profiles from our simulations and find that the profile shapes exhibit clear distinguishing features. This has been done before [28,29], but the 2D nature of those simulations precludes the development of turbulence. Also, any meaningful predictions must include thermal conduction cooling, which carries energy far from the sheet, and which dominates radiation cooling within the sheet. For our first simulations, we will maintain a constant temperature at the outer boundary, thus providing a thermal sink. Eventually, we will allow for a changing boundary temperature by coupling the MHD simulation to our EBTEL field-aligned hydrodynamics (hydro) model [30,31].

We expect the emission to be very hot, even with thermal conduction, so spectral lines in the range of 5-10 MK are especially relevant [32]. We will compare synthetic profiles with observations from spectrometers such as EIS/Hinode, IRIS, EUNIS rocket, SPICE/Solar Orbiter, and eventually EUVST/Solar-C and MUSE. This will provide a valuable test of our theoretical understanding. Note that very hot lines are less impacted by evaporated plasma along the line-of-sight (LOS) than are more traditional coronal lines at ~3 MK.

3.2 Nanoflare Frequencies and Collective Behavior (Meso Scale)

The onset conditions for fast reconnection play a primary role in determining the time-averaged heating rate in the corona. This rate is equivalent to the time-averaged Poynting flux of energy pumped into the field by photospheric driving, which depends directly on the level of magnetic stress [3]. This is only part of the story, however. The magnitudes of individual nanoflares and their repetition frequency greatly affect the radiation spectrum [32,33]. If a nanoflare releases a large amount of energy, it takes considerable time for the driving to return the field to the critical state, whereas a small energy release requires less time. Delays longer than the plasma cooling time give to rise what is known as low-frequency heating, for which the plasma cycles over a wide range of temperatures and densities. Delays shorter than a cooling time, or high-frequency heating, maintain the plasma at approximately constant conditions. Observational studies by us and others indicate a broad distribution of heating frequencies within individual active regions and a median delay comparable to a coronal cooling time [32,34,35,36].

Coronal loops – the distinct features so noticeable in coronal images – provide another key observational test. The measured lifetimes and densities of loops indicate that each one is a bundle of spatially unresolved strands [37]. We have recently studied the correlation between intensity and width along loops observed by the Hi-C rocket experiment – the highest spatial resolution coronal observations ever made – and concluded that the cross sections are approximately circular [38]. The emission can be concentrated in small irregular patches, but these patches must be distributed quasi-uniformly within an envelope that has an aspect ratio of order unity. Our second recent study using spectroscopic diagnostics is consistent with this conclusion [39].

These observations place strong constraints on the theory of nanoflares. A successful theory must explain the distributions of nanoflare energy and frequency, as well as the collective behavior responsible for loops. Meso-scale effects are involved in both. When reconnection occurs, magnetic stresses are altered in the surrounding field. Force imbalances arise, and the system rearranges on a scale much larger than an individual current sheet. This has two consequences. First, feedback on the reconnection affects how much magnetic flux is processed and how much energy is ultimately released. Second, the rearrangement modifies the conditions in nearby sheets and can bring them to the critical state, whereby an avalanche of reconnection events may ensue [40].

We have made significant progress in understanding these effects, but much more work remains. Our investigation of meso-scale effects has so far been done with the sophisticated ARMS MHD code [41]. Starting with a uniform field between two planes representing opposite polarity parts of the photosphere, we impose an array of 200 vortex flows at the boundaries, corresponding to photospheric driving. Stresses build up leading to episodes of reconnection, and a statistical steady state is achieved. In [42], we showed how helicity is transferred to the outer edge of the vortex array via "helicity condensation" [43] and demonstrated that the overall level of heating does not depend significantly on the net helicity injection, i.e., the relative proportion of left and right-handed flows. In [44], we showed that various measures of reconnection event sizes obey power-law statistics. In [45,46], we showed that the recurrence frequency of events also has a power-law distribution.

To investigate coronal loops, we must account for the response of the plasma to the heating, since magnetic strands brighten and fade over timescales much longer than the nanoflare duration [47]. This evolution depends crucially on the coupling to the transition region and chromosphere via thermal conduction, evaporation, draining, etc. ARMS presently does not include these effects, but we have devised a simple scheme that accounts for them approximately, which we perform on the MHD simulation output *post facto*. Space limitations prevent us from discussing the details, but the technique uses a cooling model applied to the average pressures integrated along field lines. Figure 2 shows a snapshot of emissivity in the midplane of the simulation box, corresponding to a vertical cut through a magnetic arcade above the photospheric polarity inversion line (PIL), as would be detected in the 193 Å channel of AIA/SDO. Notice that collections of bright emission fall within roughly circular envelopes, consistent with loop cross sections inferred from observations.

We propose several studies moving forward. First, we will impose more realistic driving. Turbulent photospheric convection causes a random walk of magnetic footpoints, which includes both rotational and translational components; so far, we have only considered the former. Adding translation will, among other things, allow us to better assess whether circular loop cross-sections are a direct reflection of the driving or a natural consequence of avalanche spread.

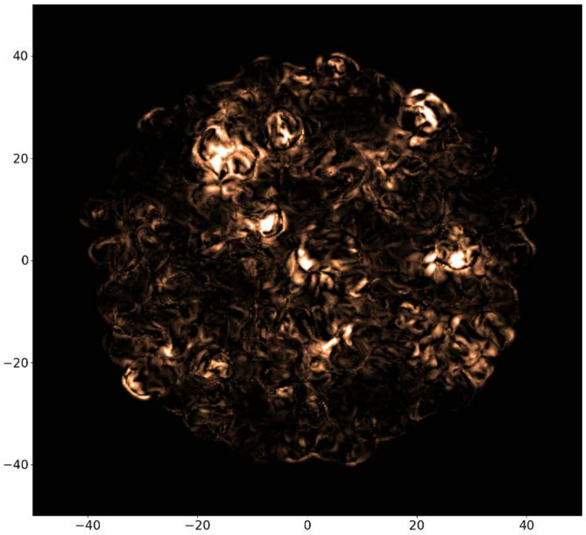

Figure 2: AIA 193 Å emissivity map corresponding to a vertical cut through the tops of loops.

Current sheets are not well resolved in our present ARMS simulations, so our second study will assess whether and how this impacts the results. The new simulations will use a similar number of grid points but have far fewer current sheets, thus corresponding to a smaller section of the active region. In addition, we will turn on explicit resistivity, not currently employed, to widen the sheets; otherwise, they tend to thin to the grid scale. We will compare the behavior, e.g., reconnection onset, to that of the highly resolved current sheets discussed in Section 3.1. This is a prime example of the interconnectedness of our program.

Third, instead of our *post facto* cooling model, we will add thermal conduction and optically thin radiation to ARMS, already in progress, so that these processes are integral parts of the MHD calculation. They are already features of LaRe3D, which we will use to perform parallel simulations. Code comparison is critical for complex modeling of this type. Each simulation will start with a fully coupled corona-chromosphere equilibrium. We will implement the TRAC technique [48], developed by team member Craig Johnston, which allows the thin transition region to be accurately treated with far fewer grid points. These state-of-the-art simulations will include evaporation and draining to provide meaningful comparisons with observations.

A fourth study involves a completely different type of model of a largely conceptual nature. Most of the plasma in the corona is contained in a “diffuse” component rather than observationally distinct loops. Is this dominant component truly diffuse and heated in a fundamentally different way from loops, or is it just a collection of loops of differing size that overlap along the LOS? There is a hint of this in Figure 2. The intensity in a single observational pixel would correspond to an integration along a vertical line in the emissivity map. Integrating along all the vertical lines would produce a 1D intensity trace perpendicular to the PIL in an image. This trace would show a smoothly varying background with occasional bumps corresponding to identifiable loops, similar to real observations [49]. We will evaluate this basic picture with a toy model consisting of a collection of filled circles of differing diameter selected randomly from an assumed distribution, e.g., a power law. We will compute LOS integrations to obtain an intensity trace, which we will Fourier analyze. We will compare the power spectrum with those from traces through real coronal images from AIA and Hi-C, thereby determining what distribution of circles (loop cross-sections) is most consistent with observations. We will perform a similar analysis on synthetic observations from our MHD simulations, providing another important test of their realism.

3.3 Height Dependence and Thermal Nonequilibrium (Meso Scale)

In addition to the cross-field spatial distribution of coronal heating (the clustering of nanoflares), the distribution of heating along the field (height dependence of nanoflares) is very important. In particular, if nanoflares occur with high frequency and at low altitude, a fascinating situation called thermal nonequilibrium (TNE) occurs [50]. TNE has been well studied in the context of steady heating. No equilibrium exists, despite the constant heating, and the plasma in a strand undergoes cycles with wide swings in temperature and density, often involving a thermal collapse and the production of a cold condensation. This is the standard explanation of coronal rain [51] and prominences [52] and has been proposed to be even more widespread [53,54]. We have recently explained the difference between TNE and thermal instability [55] and used analytical theory to determine the detailed requirements for TNE, including the effect of asymmetries [56], which we validated with 1D hydro simulations.

Although nanoflares have been shown to produce TNE, nearly all work on the subject has assumed steady heating. In contrast, most nanoflare studies have not addressed the role of their location within the strand, usually assuming uniform heating. We propose the first comprehensive study of the dependence of TNE on nanoflare properties. We will perform 1D hydro simulations with the ARGOS code [57] using different nanoflare frequencies, altitudes, and asymmetries to determine which combinations give rise to TNE. Ultimately, we will develop a unified model of the corona that allows both TNE and non-TNE behavior in a self-consistent manner. We will select nanoflares randomly from assumed energy and altitude distributions. The delay between successive events will depend on the energy of the first event, in accordance with our concept of a critical magnetic stress discussed earlier. Most of the time, a strand will undergo the usual evolution associated with nanoflares, but occasionally the conditions will be right for TNE, and the temperature and density will evolve much differently.

We will test our unified model with observations using the time-lag method we developed originally to study post-nanoflare cooling [58] and have used recently to study prominence TNE [59] and type III radio bursts from nanoflares [60]. Pairs of light curves made in different observing channels are correlated with imposed temporal offsets to find the offset that maximizes the cross-correlation power. The method identifies systematic time lags even when there are thousands of spatially unresolved and independently evolving strands [61]. When TNE and post-nanoflare cooling occur in isolation, we can easily distinguish between them using several combinations of AIA channels. However, if they occur together along the LOS, we must look at the full cross-correlation power spectrum, not just the time lag of peak power, to assess their relative roles. This enhanced approach opens a new window of possible applications. For example, we will identify both the short-term cooling associated with individual nanoflares and the long-term evolving envelope of nanoflare magnitudes, in both active regions and quiet Sun.

In addition to AIA imaging data, we will analyze spectroscopic observations, which have less area coverage, but far better temperature discrimination. We have performed a successful preliminary analysis on EIS/Hinode data and, based on that work, designed two new EIS observing programs that are customized for time-lag studies of active regions and the quiet Sun. Both programs have been run several times, and analysis of the observations is currently underway. Additional observations will be requested when suitable active regions are present.

As we and others have shown, Doppler shifts and slopes of differential emission measure (DEM) distributions also provide valuable information on nanoflare frequencies and TNE [32,62,63]. We will use these additional diagnostics to better constrain our unified model.

The unified model is hydrodynamics based, and, of course, we ultimately need to understand the MHD origin of the nanoflares and the reason for their height dependence. For this, we will use modified versions of our MHD simulations that include two additional effects: (1) the rapid expansion of the field with height as it spreads out above strong flux concentrations in the photosphere, and (2) the more gradual expansion associated with the large-scale curvature of the field. We will address the former with single current-sheet simulations like those in Section 3.1, and the latter by bending the straight field in the simulations of Section 3.2 into an arcade, such that the positive and negative polarity footpoints are on the same boundary. With this approach we can identify the physical effects most important in controlling the height distribution of nanoflares.

3.4 Active Region Models (Large Scale)

There is no question that the strength and frequency of coronal heating vary substantially across active regions and from one active region to the next [64]. However, neither the details of this variation nor its physical origin have been fully determined. The magnetic-field strength plays a major role, but other factors, such as field-line length, are also important. We have begun to address these open questions using the following modeling approach. The effort stems from our involvement in the development of the new GX_Simulator community tool [65], led by New Jersey Institute of Technology. The “magnetic skeleton” of an active region is constructed from an observed photospheric magnetogram using a force-free extrapolation. Field lines are populated with plasma using our EBTEL hydro code, another community tool, based on nanoflares with assumed properties, such as a power-law energy distribution. A corresponding distribution of frequency based on the concept of critical stress provides the desired time-averaged heating rate. A crucial aspect is that the time-averaged heating rate depends on the local properties of the magnetic field, such as its strength and field-line length, in a manner specified by the user, e.g., $H \propto B^{\alpha}L^{\beta}$. Simulated observations are produced, including EUV and radio images. By comparing them with real images and varying the assumed properties of the nanoflares, we will identify the actual properties. An example comparison is shown in Figure 3 for the AIA 211 Å channel. No attempt was made to fine tune the parameters to maximize the agreement. The inclusion of the transition region is essential to our model. This thin layer where thermal conduction is a source of energy (rather than sink, as it is in the corona) can reach very high temperatures (roughly half the peak temperature of a strand [30]). The transition region therefore contributes strongly to the emission detected in all AIA channels, even those considered to be “coronal” [33].

There are two benefits to this modeling approach. First, and of primary interest to us initially, are the unparalleled physical insights about nanoflares and their observable properties.

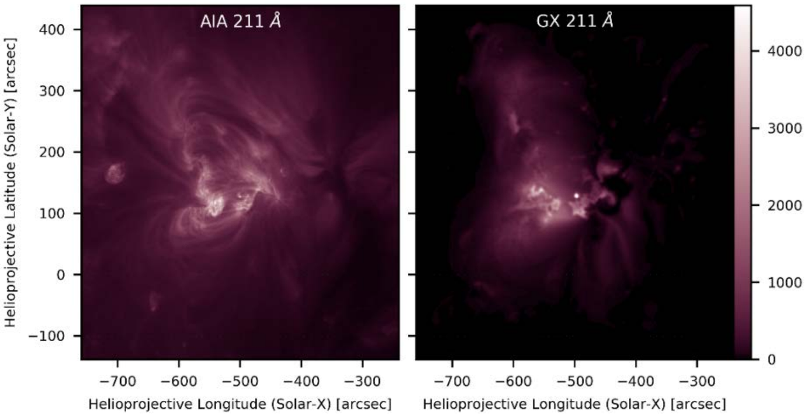

Figure 3: Observed (left) and synthetic (right) images of an active region in the 211 Å channel of AIA, with peak sensitivity at ~2 MK. Intensity scale (DN/s) at right.

Second, if we can establish the properties of nanoflares, even without knowing their physical origin, we can predict the solar spectral irradiance. One can easily imagine successor models being used in operations to nowcast and even forecast the spectral irradiance.

In summary, we will use a coordinated combination of theory, modeling, and observations to reveal and explain the properties of nanoflares, ranging from the smallest scales that control the onset of magnetic reconnection, to meso scales that determine how nanoflares interact and produce the plasma conditions, to the largest scales over which the properties vary systematically. Ultimately, we seek a **comprehensive understanding of how the magnetically closed corona is heated**.

A complete picture must include wave heating. Although a variety of evidence suggests that wave heating is weaker than reconnection heating [4], their relative importance has not yet been firmly established. Furthermore, reconnection heating and wave heating are not necessarily independent. Waves are generated by high-frequency motions in the photosphere, but they are also generated by reconnection in the corona and below. Both forms of heating are impulsive and occur on small cross-field spatial scales (waves dissipate by resonance absorption, phase mixing, and/or turbulent cascades). Therefore, the observational and hydro modeling studies proposed in Sections 3.3 and 3.4 apply equally well to wave heating. We have added Ineke De Moortel to our team. She is an internationally recognized expert on wave heating who will advise us on the possible role of waves in our investigations. For example, she will evaluate whether wave heating is consistent with the observationally inferred macro and large-scale properties. If warranted, we will expand our modeling to include waves explicitly.

4. ISFM Relevance

4.1 Strategic Scope

Coronal heating is one of the great unsolved problems in space science. It is a primary motivation for many past, present, and planned missions, including SDO, IRIS, Hinode, Solar Orbiter, PSP (magnetically open corona), Solar-C, and MUSE. Magnetic reconnection is a fundamental process responsible for many heliophysical and astrophysical phenomena, so by studying nanoflares we can develop physical insights of widespread importance. Coronal heating powers the X-ray and UV radiation from the Sun, which is an important driver of the terrestrial upper atmosphere and has major space weather impacts, especially in the areas of communication, navigation, and spacecraft collision avoidance. There are also important implications for the development of life around the universe. Our work package directly addresses the two Decadal Survey goals related to fundamental physical processes and origins and impacts of solar activity.

As we have emphasized, the coronal heating problem has many aspects, involving an enormous range of spatial scales and different types of physical coupling. Only by addressing all these aspects in an integrated way can a comprehensive understanding be achieved. Our work package is unique in this regard, allowing us to make great progress not otherwise possible.

4.2 Why Goddard?

Because of the complex and multi-faceted nature of the problem, a well-coordinated team approach is crucial. Goddard is best positioned to achieve success. No other group in the world has our combined expertise in theory, 3D MHD and field-aligned hydro simulations, EUV spectroscopy and imaging, and space weather applications. All must be brought to bear on the problem. We also benefit from many Goddard colleagues working on related heliophysics problems, e.g., magnetospheric substorms, and from the Community Coordinated Modeling Center. The ability to easily hold formal and informal meetings and to walk down the hall to have impromptu discussions at the white board is invaluable.

4.3 Community Service

As has been emphasized to us many times by ISFM program managers, the most valuable service we can provide is the advancement of physical understanding for the benefit of the entire science community. We have been extremely successful in this regard, and our detailed research plan will allow us to continue this success moving forward. It is worth noting that we are internationally recognized leaders in this research area, having been invited to present keynote addresses and write most of the major review articles on the topic in recent years [1,2,3,4,32].

We are committed to training the next generation of heliophysicists. Our current team includes junior scientists Kalman Knizhnik and Samuel Schonfeld, graduate student Sherry Chhabra, high school intern Ananya Iyer (two summers), and undergrad intern Carina Alden. Kalman and Sam will continue, and we welcome new post-doc Craig Johnston.

The Coronal Loops Workshop Series is the main venue for focused discussions on the heating of the magnetically closed corona (the initial scope has expanded from loops). We have been very active in the organization of these highly anticipated workshops. The series was founded by PI Klimchuk in 2002, and we have served as members of the steering committee and scientific organizing committee (SOC), including at the present time. Klimchuk also started the Triennial Earth-Sun Summit (TESS) meeting series, which covers all heliophysics and reflects our commitment to bringing the community together to share ideas for the benefit of everyone. He serves on the SOC for the TESS meeting next summer.

We have and will continue to make improvements to several simulation codes used by the broader community. Our active region study discussed in Section 3.4 uses the recently released GX_Simulator modeling tool, now being applied to multiple problems. The fidelity of the models depends sensitively on the assumed form of coronal heating. We played a major role in developing this aspect of the tool [65] and are presently involved in the implementation of new features. Our EBTEL hydro code [30,31] is at the core of the GX_Simulator plasma model and has been widely used by the solar community for many years. We are now working with others to improve EBTEL by adding variable cross sections and kinetic energy. We developed the TRAC method [48] for treating the transition region in a computationally efficient manner and plan to incorporate it into the LaRe3D and ARMS MHD codes. The broader community uses all these codes and will benefit greatly from our efforts.

As we have discussed, the conditions that control the onset of fast reconnection are crucial to the buildup and release of magnetic stress. They determine the energies of nanoflares, CMEs, flares, jets, and many other phenomena. We will strive to develop a parameterized method of incorporating onset conditions into MHD simulations that cannot adequately resolve the current sheets that are present. This is sometimes referred to as sub-grid physics. If successful, this will be a major breakthrough that benefits the entire modeling community.

The active region models discussed in Section 3.4 can one day be transitioned to operations for nowcasting and forecasting the solar spectral irradiance. To help guide us toward this future goal, we have added Yihua Zheng to the team. She is a member of Goddard's Community Coordinated Modeling Center and a key person in their space weather activities. She is our direct link to both the ITM research community and the civilian space weather user community. Continuing team member Schonfeld, who recently finished a post-doc at Goddard and started a new position at the Air Force Research Lab, will be our link to the DoD user community.

Two years ago, we convened a successful one-day workshop on "Impacts of Intermediate Timescale Solar Spectral Irradiance Variability" that brought together two dozen experts from the solar and ITM communities, with additional participation from the user community (https://science.gsfc.nasa.gov/670/variability_workshop/). We plan to continue these workshops on an annual or biennial basis, with even stronger participation from the user community.

We have and will continue to support the development of new instruments and mission concepts. We played major roles in the EUVST/Solar-C, VISORS/Cubesat, FOXSI/SMEX, and FIERCE/MidEx proposals. All four had nanoflares as a major science objective. EUVST and VISORS were selected, with EUVST now undergoing concept study review. FOXSI and FIERCE received high ratings, though were not selected. We will support future opportunities as they arise.

5. Plan of Work and Management Structure

Major progress on the coronal heating problem requires a comprehensive approach, and we have assembled a team with all the skills necessary to be successful. The effort is led by PI James Klimchuk, who will oversee the entire program and play an active role in each of the individual investigations. Though he works closely with observations, his emphasis is on theory. To balance the leadership team, Therese Kucera, an expert in observations, is the Deputy-PI.

The MHD simulations will be performed by James Leake, Lars Daldorff, Kalman Knizhnik, and Craig Johnston. Leake and Knizhnik have vast experience using LaRe3D and ARMS, respectively, on a variety of solar problems. Daldorff is an expert on numerical algorithms who has used and modified many codes, including these two. He is highly knowledgeable about the strengths and weaknesses of simulations and will ensure that our results are robust. He is also an expert on PIC and embedded-PIC codes, should the need arise. Johnston will implement his TRAC technique for treating the transition region into both LaRe3D and ARMS. Initially, Leake and Daldorff will concentrate on the single current-sheet simulations of Section 3.1, while Knizhnik and Johnston will concentrate on the multi-strand/multi-sheet simulations of Section 3.2. We will follow the science and redistribute the workload as appropriate. The tasks in 3.1 are partially supported by a Living With a Star grant, though that effort is much more general than coronal heating. Klimchuk and Vadim Uritsky will be active in the design, analysis, and interpretation of all the simulations. Uritsky will continue to develop the semi-analytical model of the diffuse corona discussed in Section 3.2 and will apply it to imaging data from Hi-C and AIA/SDO with help from Klimchuk and Nicholeen Viall. Jeffrey Brosius, Peter Young, and Kucera have great experience with EUV spectroscopy from many missions, including EIS/Hinode, EUNIS, and now SPICE/Solar Orbiter. They will conduct the observational comparison with hot (> 5 MK) line profiles predicted with the MHD simulations.

Klimchuk and Judith Karpen have a long history using the ARGOS 1D hydro code, and Johnston is experienced with the competitor HYDRAD code. With help from them, Kucera will run the simulations of nanoflares and TNE described in Section 3.3. Observational tests using the time-lag method will be performed on EIS and AIA data by her, Brosius, Viall, and Klimchuk. Brosius created the new EIS observing programs designed for this purpose. Viall and Klimchuk developed the time-lag method and know best how to extract maximum information with it, as will be needed to fully evaluate the unified model that includes both TNE and non-TNE behavior. Additional tests based on Doppler shifts and differential emission measure slopes will be performed by Kucera, Brosius, and Young.

The active region modeling study described in Section 3.4 was started by Samuel Schonfeld and Klimchuk. It will be taken over by Young, but Schonfeld will continue to collaborate from his new position at AFRL. He will be our liaison to the DoD user community as we consider the space weather applications. Yihua Zheng will play that role for the civilian user community. Klimchuk and Zheng will organize the solar spectral irradiance variability workshops with help from Schonfeld.

Ineke De Moortel is our waves expert who will advise us on the potential role of waves in all our studies. She will recommend specific modeling and observational areas to pursue.

As we have emphasized, different aspects of coronal heating can be studied in detail only by treating them individually. At the same time, these different aspects influence each other, often dramatically. Our program is unique in that we take a wholistic approach; all the investigations are interconnected. For example, the multi-current sheet simulations in Section 3.2 must obey the reconnection onset conditions identified in Section 3.1, and the nanoflares in the MHD simulations must have the same properties as determined from observations and hydro modeling in Sections 3.3 and 3.4. All pieces of the puzzle must ultimately fit together, and team coordination is key.

To facilitate this coordination, our full team meets on a semi-regular basis (approximately every 2-3 weeks). Subgroups meet much more frequently, even daily, depending on the rate of progress. Productivity is enhanced by having everyone collocated in the same building. For example, impromptu discussions at the white board have proved extremely valuable. Knizhnik works “down the street” at NRL, but he visits Goddard regularly. De Moortel and Schonfeld will participate in meetings remotely and will make trips to Goddard as necessary. Our productivity over the past 3 years attests to the effectiveness of our management approach.

We maintain a team website where we post presentations from our team meetings and a list of papers and presentations given at conferences and workshops: https://science.gsfc.nasa.gov/670/variability_workshop/heating.html.

6. Annual Milestones and Deliverables[1]

Year 1:

S: Single current sheet simulations with (1) thinning and (2) line-tying.
S: Synthetic spectral line profiles from single-sheet simulations with constant-T boundary
MM: Multi-strand simulations with realistic driving (translation and rotation).
MM: Adding TRAC to LaRe3D and ARMS.
MA: Semi-analytical model of diffuse corona (overlapping loops).
MH: Nanoflare hydro simulations to determine conditions required for TNE.
MH: Improvements to EBTEL.
M: Observed time lags in quiet Sun using EIS/Hinode spectral line data for
M: comparison with nanoflare hydro and multi-strand simulations (years 2 and 3).
L: Models of one observed active region using different nanoflare properties and
L: comparison with AIA imaging observations.
L: Improvements to GX_Simulator
L: Solar spectral irradiance workshop.

Year 2:

S: Single current sheet simulations with footpoint driving.
S: Comparison of synthetic and observed line profiles (EUNIS, EIS/Hinode, IRIS, SPICE/SO).
MM: Multi-strand simulations with fewer strands and improved resolution of current sheets.
MA: Comparison of diffuse corona model with imaging observations (Hi-C, AIA).
MH: Unified nanoflare model and comparison with time lag observations.
M: Observed time lags in active regions using EIS/Hinode spectral line data for
M: comparison with nanoflare hydro and multi-strand simulations and AR models (year 3).
L: Models of one observed active region using different nanoflare properties and
L: comparison with spectroscopic observations (time lag, DEM slope, and Doppler shift).

Year 3:

S: Single current sheet simulations with finite length.
S: Sub-grid parameterization model of reconnection onset conditions.
S: Synthetic line profiles from single-sheet simulations with nonuniform & evolving boundary T
MM: Multi-strand simulations with stratified atmosphere, thermal conduction, radiation and
MM: comparison with imaging and spectroscopic observations.
MH: Unified nanoflare model and comparison with DEM slope and Doppler shift observations.
L: Models of several observed active regions of differing size, age, and complexity and
L: comparison with imaging and spectroscopic observations.
L: Solar spectral irradiance workshop.

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[1] S: small-scale (Sec. 3.1); MM: meso-scale MHD (Sec. 3.2); MH: meso-scale hydro (Sec. 3.3); MA: meso-scale analytical (Sec. 3.2); M: meso-scale observations; L: large-scale (Sec. 3.4)

7. Results and Findings of Ongoing Work Package

Three years ago, we laid out an ambitious, long-range plan to explain how the magnetically closed corona is heated. We have made excellent progress, despite being funded at half the requested level and 1/3 to 1/2 the level of most other work packages. We published 16 papers and gave 62 presentations (including coauthorship, but not presentations at team meetings). See https://science.gsfc.nasa.gov/670/variability_workshop/heating_presentations/papers_presentations_numbered.pdf. We made major advances in all four areas of Section 3, as well as other closely related areas not discussed there due to space limitations. We now summarize our major findings.

Using highly resolved, state-of-the-art 3D MHD simulations of individual current sheets, we made a major breakthrough in understanding the onset of fast magnetic reconnection [19], a key to explaining the buildup and explosive release of magnetic energy responsible for nanoflares and many other phenomena. We developed a conceptual physical framework that, for the first time, organizes the variety of often confusing behaviors reported in the reconnection literature. What is especially exciting is that we can predict whether and how a current sheet will reconnect (turbulence or coalescing plasmoids) based on its width, length, and shear angle. We have generated synthetic EUV spectral line profiles from some of our simulations and find that they offer great diagnostic potential for distinguishing the different forms of reconnection. Profiles from future simulations with cooling will be compared with observations to provide a crucial test of our understanding.

We used MHD simulations of systems with multiple current sheets to investigate the multi-stranded nature of the corona. We found that nanoflares obey power-law statistics [44], have a range of repetition frequencies that also obey a power law [45,46], and do not depend strongly on the net helicity of the footpoint driving (proportion of magnetic strands with left-handed and right-handed twist) [42]. Using a simple cooling model applied *post facto* to the MHD simulation output, we showed that the EUV emission expected from clusters of nanoflares forms patterns consistent with those we inferred from coronal loop observations. We concluded based on two different observational approaches – one involving high-resolution Hi-C images [38] and the other involving EIS/Hinode spectroscopy [39] – that the cross-sections of loops are approximately circular, just as in the simulations. We also studied the differential emission measure slopes expected from the simulations and compared them to observed values [46].

We used field-aligned hydrodynamics modeling to investigate a variety of observational signatures of nanoflares and thereby determine their physical properties. One important diagnostic is the time lag between light curves obtained in two different observing channels, a method that we pioneered. In [62], we employed machine learning to relate time lags and differential emission measure slopes to nanoflare properties. In [63], we studied Doppler shifts and broadening of coronal spectral lines. We also studied the Doppler shift of a lower transition region line observed by IRIS and concluded that the emission comes primarily from type II spicules [66]. In [67], we compared predicted and observed hard X-ray thermal spectra from the FOXSI rocket and NuSTAR mission. In [33], we examined the relative contributions of coronal and transition region emissions to intensities observed by AIA/SDO. And we have begun to model active regions with the GX_Simulator tool and to compare predicted and observed AIA images. In all these studies, the observational diagnostics were shown to be sensitive to the assumed properties of the nanoflares, such as their frequency of occurrence. Where comparisons were made with actual observations, the overall trends are consistent. Active regions display a range of nanoflare frequencies, with some more weighted toward high frequency and others more weighted toward low frequency.

A long-standing question is whether nanoflares accelerate particles to high energy like regular flares. Lack of strong nonthermal emission in hard X-rays rules out many very high energy particles, but substantial numbers of mildly nonthermal particles could be present. These are best detected by the type III radio bursts that they produce. Since nanoflares are so copious, the bursts would be overlapping and impossible to detect as individual events. Fortunately, they exhibit a distinctive frequency drift with time, and our time lag technique applied to light curves at different radio frequencies can detect them despite the overlap. We have constructed detailed models of overlapping bursts to identify their signature in time lag cross-correlation power spectra [60] and are now comparing them with ground-based and Parker Solar Probe radio observations.

We made major progress in understanding the fascinating phenomenon of thermal nonequilibrium (TNE). We explained how it is different from, though similar to, thermal instability [55], and we derived analytical formulae for the steady heating conditions needed to produce TNE, including the important role of asymmetries [56]. We performed a time-lag analysis on synthetic and actual AIA observations to investigate the signatures of TNE in and near solar prominences and confirmed that prominences are indeed formed by this process [59].

We wrote two invited review papers on coronal heating in general [4] and nanoflares specifically [32].

Despite this great progress on multiple fronts, it is only a start. Our MHD simulations must be improved with new levels of realism in several important ways before our interpretations and conclusions can be considered definitive. This includes time-dependent thinning and shearing of individual current sheets, and more realistic driving and improved resolution in multi-strand, multi-sheet simulations. Thermal conduction cooling and coupling between the corona and chromosphere must be added to provide more meaningful comparisons with observations.

On the scale of active regions, we have only started to explore the relationship between nanoflares and their observational signatures. We must apply quantitative observational tests of the models to determine the properties of the nanoflares and their systematic variation within active regions and among active regions of different size, complexity, and age. Only then can we hope to make serious predictions of the solar spectral irradiance.

Our studies of TNE have concerned high-frequency (steady) heating, yet we know that a wide range of frequencies are present in each active region. We must determine the conditions under which nanoflares give rise to TNE. Can a universal model that self consistently includes both TNE and non-TNE behavior provide a better agreement with the observations? Our new, custom designed EIS/Hinode observing programs will be of great value in answering this question.

The coronal heating problem is complex and demands a multi-pronged approach. Our carefully planned and coordinated modeling (MHD and hydrodynamic), combined with rigorous observational testing (imaging and spectroscopic), has proved very effective so far. By continuing on this path with a clear strategy, while being flexible to respond to new insights and discoveries, we expect to achieve a comprehensive understanding of how the magnetically closed corona is heated to its multi-million degree temperatures, i.e., to finally solve the coronal heating mystery!

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