Team Charter:

Heliophysics Living With a Star (H-LWS) Science Program NNH18ZDA001N-LWS

FST#4: Understanding Global-Scale Solar Interior Processes and the Implications of Changes in the Solar Interior on the Heliosphere

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Introduction:

In order to understand the origins and evolution of solar magnetic activity occurring on a wide range of time-scales, and the space weather caused by the particulate and electromagnetic outputs that reach the Earth, we need to understand the physical origins of this activity below the photosphere. While it is generally agreed upon that the solar convection zone and the tachocline at its base contain a magnetohydrodynamic dynamo that produces, sustains and evolves the magnetic features we see at the surface and in the corona, the processes that are responsible for driving the solar interior MHD processes are not directly observed. Although much progress has been made in understanding these processes and their relation to observed solar flows and magnetic activity, our understanding is far from complete, due to lack of consensus in observations of solar interior flows. The main objective of our focused science team is to jointly develop the most comprehensive, dynamically consistent picture possible of solar flows at the surface, in the convection zone and tachocline, and determine the MHD effects induced by these motions. We will do this by building and/or employing MHD models capable of operating in data-driven and data-assimilative modes. In pursuing this objective, our FST team will work to develop consensus sets of observational constraints and simulate model-outputs of magnetic activity and flows which can reliably be used as inputs to heliospheric and terrestrial-atmospheric models. The ultimate test of our success will be the development of significant improvements in our ability to predict the features of solar cycle 25, including the active latitudes and longitudes, global and localized flows several months ahead. The various research groups included in this team cover all the observational and modelling capabilities, so all the essential components of expertise are present.

1. What are our Objectives? (Define the purpose and mission of the team)

The main purpose of FST#4 of LWS-2019 is to understand global solar processes in the solar interior and their impact on the solar surface and heliosphere.

Mission of the team: Investigate solar interior dynamics and develop a data-driven model for forecasting active regions emergence several months ahead of time, and explore their impact on heliosphere as well as their role in space weather.

2. What are our Goals? (Define how the team will know that they have been successful. Discuss Individual values and goals and ensure that they align with the overarching larger team goals.)

Overarching goal(s): To advance our understanding of large-scale internal dynamics, magnetic flux creation and emergence, by linking global flows and localized active regions' flows with short- and long-term magnetic variabilities, for forecasting/simulating reliable solar inputs to heliospheric and terrestrial models.

Three sub-goals of our FST#4 team under this overarching goal are:

Sub-goal 1. Develop a consensus set of observational constraints of surface and interior flows, including hemispheric and latitudinal dependence.

Sub-goal 2. Model global magnetic activity and flows of the solar interior and assimilate observations into those models.

Sub-goal 3. Simulate active latitudes and longitudes during the next solar cycle and predict the magnitude and timing of the next solar maximum

3 & 4. Who are involved, who will do what?

Teams and individual goals:

(i) Lisa Upton (SSRC), PI
Team-members: Co-I Derek Lamb (SWRI)

Project: Improving Long Term Forecasts of Solar Variability with the Advective Flux Transport Model

Individual goals:

- Perform feature tracking of magnetic network patterns to obtain improved surface measurements of the Differential Rotation and the Meridional Flow and their temporal variations, including the torsional oscillation
- Perform feature tracking on faculae with SWAMIS to measure flow velocities of these

features.

- Compare the flow velocities measured with these techniques to access the uncertainty and improve estimates of the surface flows, particularly at latitudes above 60º.
- Characterize the large, long-lived convective cells and investigate the relationships between the emergence and evolution of the magnetic field.
- Provide an ensemble of predictions for the magnitude and timing of the polar field evolution and Solar Cycle 25 maximum.

(ii) Haimin Wang (NJIT), PI
Team-members: Co-Is Phil Scherrer and Junwei Zhao (Stanford), Yan Xu (NJIT), collaborators Dipankar Banerjee (Nainital & IIA, India), Carsten Denker and Meetu Verma (AIP, Potsdam), Postdoc Qin Li (NJIT).

Project: Study of Global-Scale Surface Flows and Migration of Polar Crown Filaments of the Sun in Past 10 Solar Cycles in Comparison with Helioseismology Results in 2 Recent Cycles

Individual goals:

- Provide global flow measurements as input for dynamo and solar cycle modeling.
- Investigate the effects of global-scale flows and polar crown filament migrations on different amplitudes of solar activity.

(iii) Yang Liu/ Phil Scherrer (Stanford), PI
Team-members: Co-Is Marc De Rosa (LMSAL), Todd Hoeksema (Stanford), Junwei Zhao (Stanford) Xudong Sun (U Hawaii).

Project: Linking Active Regions and Solar Cycles to Understand How Variable Flows in the Solar Interior Affect Surface Magnetic Field Evolution

Individual goals:

- derive observation-based surface flow profiles that are modulated by property of magnetic field in active regions;
- incorporate the derived flow profiles with a surface flux transport (SFT) model to study flux evolution and polar field reversal;
- use the SFT to predict solar cycles.

(iv) Doug Braun (NWRA), PI
Team-members: Co-I Matthias Rempel (HAO/NCAR)

Project: Active Region Dynamics and the Variability of Meridional and Zonal Flows

Individual goals:

- Characterize, through ensemble averaging of 100s-1000s of holography-derived flow maps, the near-surface flows around active regions, as functions of magnetic and evolutionary properties;

- Establish and quantify the contribution of near-surface flows around ARs to latitudinal and temporal variation of global zonal and meridional flows, on a rotation-to-rotation time frame;
- Explore and characterize holography-inferred flows around high-latitude flow anomalies (“giant cells”);
- Infer depth variation of ensemble-averaged flows for ARs and giant cells;
- Simulate flows around ARs to 1) provide validation of flow inferences, 2) understand physics of AR inflows.

(v) Nick Featherstone (CU), PI
Team-members: Co-Is Ben Brown (CU), Brad Hindman (CU), postdoc (TBD)

Project: Processes Shaping the Solar Meridional Circulation

<u>Individual goals:</u>

- Examine how the convection zone’s boundary layers (tachocline and near-surface shear layers) impact the properties of meridional circulation
- Identify trends in the circulation morphology related to a changing Ro with depth
- Identify trends in the response of meridional circulation as the stiffness (entropy gradient) of the stable region is varied
- Find out if there are convective structures or large-scale flow patterns that develop which may be directly compared to helioseismic observations
- Systematically examine how magnetism influences aspects of the convection, and how it modifies the influence of the near-surface and stable regions.
- Impact of magnetism on the scaling trends already observed for kinetic energy and characteristic convective spatial scale in hydrodynamic system
- Investigate how the meridional circulation and differential rotation are altered in the presence of magnetism, and whether the flow morphology is a diagnostic of the Sun’s dynamo state
- Explore the role of cyclic magnetic field on the temporal evolution of the meridional flow and vice versa

(vi) Rudi Komm (NSO), PI
Team-members: Co-Is Kiran Jain, Sukur Kholikov, Sushant Tripathy (NSO)

Project: Do Flows in the Upper Solar Convection Zone Drive Global-Scale Magnetic Fields?

<u>Individual goals:</u>

- Determine the dynamics of large-scale subsurface flows near locations of recurring magnetic activity, such as activity complexes, and search for subsurface markers or even precursors of magnetic activity.
- Determine the solar-cycle variation of subsurface flows, its strength and organization, isolate the contributions of active regions, and determine the strength of the global component that is unrelated to active regions.
- Determine the North-South asymmetry of flux and subsurface flows, compare the magnetic activity and their associated subsurface flows in different latitude regimes, and establish how well these flows work as precursors of the next-cycle activity.

- Determine the flows at mid- to high latitudes where the equatorward branch of the flow pattern appears years before the activity of the next cycle is present and evaluate the poleward branch of the flow pattern and its timing with regard to the build-up of polar fields.

  (vii) Mausumi Dikpati (HAO/NCAR), PI
  Team-members: Co-Is Jay Johnson (Andrews Univ.), Robert Leamon (Maryland), Scott McIntosh (NCAR), Aimee Norton (Stanford), Phil Scherrer (Stanford), Simon Wing (JHU/APL)

Project: Simulating active longitudes by coupling magnetograms with a nonlinear MHD tachocline model: a data assimilation approach

Individual goals:
- Simulate latitude-longitude locations and strengths of active regions from nonlinear dynamical evolution of spot-producing toroidal fields at the convection-zone base
- Build a forward operator using information theoretic approach to connect magnetic "imprints" from tachocline-top to the solar surface
- Assimilate magnetogram observations to estimate time-lag between surface active regions and that derived from model-output
- Infer properties of global and localized flows in from model-output and compare with observations
- Simulate evolutionary pattern of active regions during rising, peak and declining phases of solar cycle

5. Identify detailed actions for reaching each sub-goal along with required team interactions (individual, sequential, reciprocal, simultaneous)

5(a) Detailed science plan for sub-goals:

Sub-goal 1: Develop a consensus set of observational constraints of surface and interior flows, including hemispheric and latitudinal dependence.

All models (surface flux-transport, 3D dynamo and 3D MHD tachocline models) to be used by our FST team use somewhat different data. Although the surface flux-transport models will use surface flow velocity and magnetic data, all three types (direct Doppler, helioseismic and feature tracking) are relevant. Dynamos will need time dependent interior velocities, including differential rotation, meridional circulation, and longitude-dependent localized flows in and around active regions, which modulate the global flows. MHD tachocline models will use helioseismic data that has information about the bottom of the convection zone and tachocline, as well as magnetogram data. To solidify the consensus data set, where multiple types of data have information about velocities for the same locations, comparisons will be made to determine the best quality picture.

We define **"Action Team 1"**, consisting of the following teams: Wang (NJIT), Braun (NWRA/CORA), Komm (NSO), Upton (SSRC), Liu (Stanford). Action Team 1, for investigating global and localized flows, primarily lead the sub-goal 1, and will contribute to sub-goals 2 and 3. Braun's and Komm's teams have components for "Simultaneous work (Si)"; both teams will derive flows in and around active regions or activity-belts, using different methods. Whole Action Team 1 will interact sequentially with Action Teams 2 and 3, providing their products to be used as input for performing comparison, assimilation components in sub-goals 2 and 3.

Major activities and time frames of Action Team 1:

a) Derive global flow measurements (meridional circulation, differential rotation, and large scale convection) from long-term data (1st and 2nd year)
b) Compare measured localized flows in and around activity-belts (1st and 2nd year)
c) Provide consensus measured flows for use in models for performing actions in sub-goals 2 and 3 (3rd and 4th year)
d) Develop a consensus set of measured global and localized flows (4th year)

Sub-goal 2: Model global magnetic activity and flows of the solar interior and assimilate observations

From a physical modeling point of view, the solar interior (the convection zone including the two boundary layers, i.e. the tachocline at the bottom and the near-surface shear layer at the top) is most plausibly the place, where major global MHD processes are occurring. To investigate the generation and evolution of interior flows and magnetic activity, we will build/employ MHD models of the convection zone and tachocline, and simulate the global flows and magnetic fields, as well as their connections with surface emergence of active regions', their locations and timing, and localized flows in and around active regions. We will compare model-outputs with observations derived from our sub-goal 1, and to be able to predict we will assimilate observations, taking input from the output of Action Team 1 and also various other observations (i.e. SoHO/MDI and SDO/HMI magnetograms). The observations will be adapted to the different domains the various models are applicable to. Spatio-temporal resolutions needed for assimilation will be determined by the range allowed by the original observations, with appropriate smoothing and/or running averages.

We define **"Action Team 2"**, consisting of the following teams: Featherstone (CU), Dikpati (HAO/NCAR), Upton (SSRC), Li (Stanford). Action Team 2, for investigating modeling and assimilation, will lead sub-goal 2 and will interact sequentially (Se) with Action Teams 1 and 3, respectively by using products of Action Team 1 as input to data-driven/data-assimilative components in model-simulations, and by contributing model-outputs to Action Team 3. Featherstone's and Dikpati's teams have components for "Reciprocative works" (R); one's model-output can be used as input into other's model.

Major activities and time frames of Action Team 2: (Nick please add/modify activities in bulleted form, and anticipated time frames)

a) Simulate dynamical evolution of spot-producing toroidal fields; generate "imprints" of locations of magnetic flux emergence from tachocline MHD model-output (1st and 2nd years)
b) Perform reciprocative researches on MHD of tachocline model and 3D convection zone dynamics (throughout the project), namely

- Explore, by incorporating time-varying magnetic boundary conditions from MHD tachocline models in global convection models how global-scale flows, particularly meridional circulation, are modified; does that induce torsional oscillations?
- Explore, by incorporating statistics of overshooting motions from convection models, how MHD tachocline model-outputs for magnetic patterns differ.

c) Take input from products of sub-goal 1, and assimilate into models to test predictive capability for time and locations of active region eruption (3^{rd} and 4^{th} years)
d) Provide simulated magnetic flux distributions (latitude-longitude, size and strength) and timing for using as input "active regions" in performing sub-goal 3 for predicting cycle 25 features (3^{rd} and 4^{th} year)
e) Generate a set of global MHD convection-zone models that extend close enough to the photosphere to be compared with and constrained by ongoing local helioseismic observations (4^{th} year)
f) How do we incorporate Large Scale Convection Observations?

Sub-goal 3: Simulate active latitudes and longitudes during the next solar cycle and predict the magnitude and timing of the next solar maximum

Surface flux-transport models, capable of running in data-driven/data-assimilative regimes, will use observational input from sub-goal 1 as well as various other observations. These models will produce solar magnetic activity evolutionary properties at the surface, their roles in polar fields and solar cycle. Each model, driven by relevant data and/or data assimilated, will be run for a number of years, creating an ensemble of simulations that can be extended into cycle 25. Each model will yield predictions of variables, which will be compared to the actual evolution of solar activity over the next several years, into cycle 25. The quantities predicted from the output of the models with more degrees of freedom and dimensions can be averaged to yield derived output that can be compared to that from the models with fewer dimensions. For example, surface flux-transport model output will be compared with longitudinally averaged output, mapped to the surface, from 3D convection and tachocline models.

We define **"Action Team 3"**, consisting of the following teams: Upton (SSRC), Liu (Stanford), Dikpati (HAO/NCAR), and Wang (NJIT). Action Team 3, for investigating simulations and predictions, will lead sub-goal 2, and will work sequentially (Se) with Action Teams 1 and 3, in the form of using inputs and contributing their outputs. Upton's and Liu's teams have components for "Simultaneous works" (Si); both have their respective surface flux-transport models, the outputs from which can be compared back and forth.

Major activities and time frames of Action Team 3:

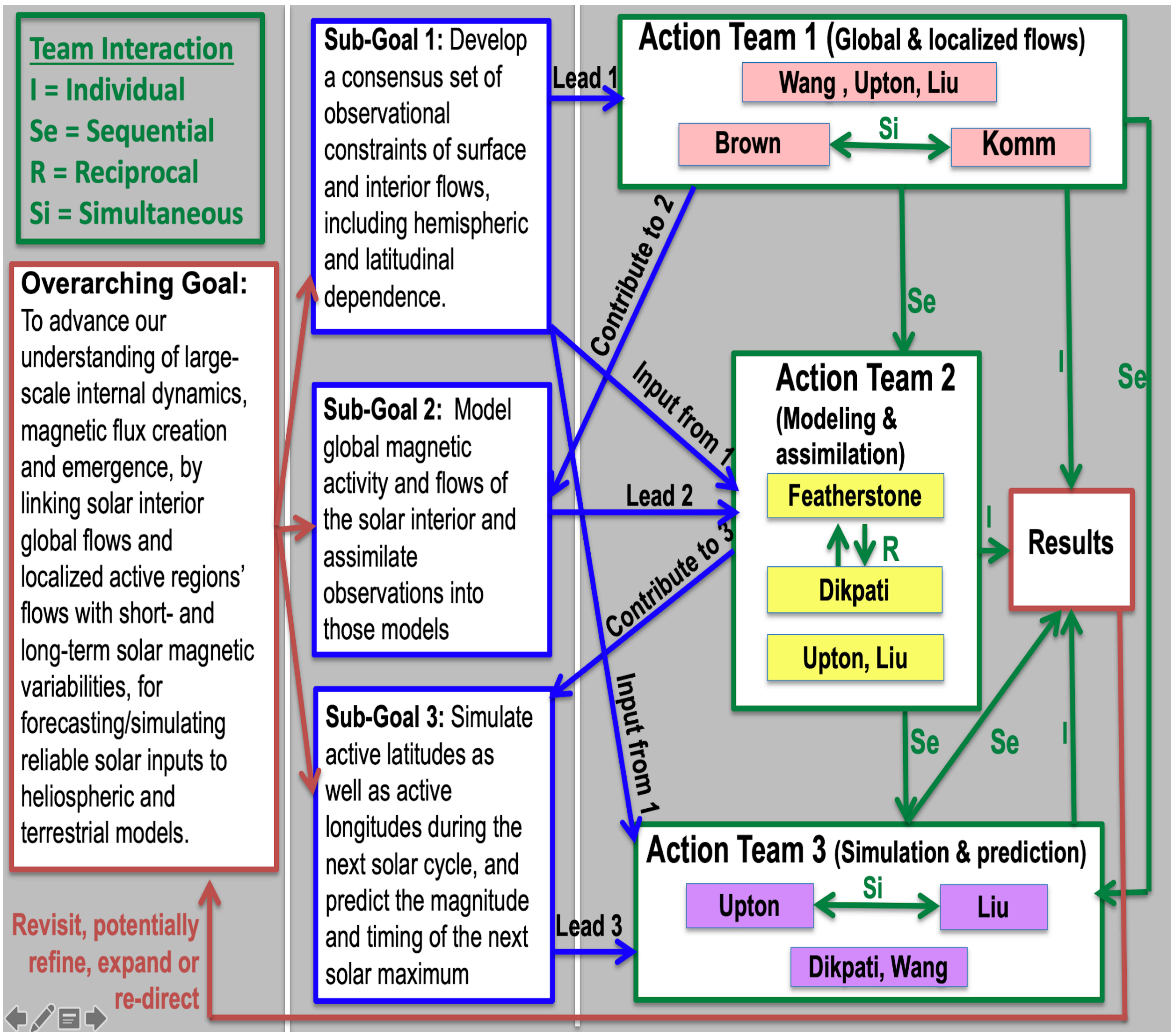
a) Simulate evolution of polar fields from surface flux-transport models (1^{st} & 2^{nd} year)
b) Estimate how the localized flows in and around active regions may modify the global meridional circulation (1^{st} year)
c) Take input from sub-goal 2 and run SFT models using observed and "synthetic" (model-generated) active regions emergence and compare with observations (3^{rd} and 4^{th} year)
d) Compare model-outputs from 3D models averaged over longitudes to SFT model-outputs and find out what we can learn from differences, expecting there would be some but not a lot of differences (3^{rd} and 4^{th} year)

e) Run SFT models in data-driven regimes, simulate polar fields, active latitudes and cycle 25 strength (4th year)

f)

5(b). Team-collaboration flow-chart along with required team interactions (individual, sequential, reciprocal, simultaneous)

Establish specific Goal for FST team of teams; break the Goal down into specific concrete and attainable sub-goals; identify detailed actions - and the who, when, and where – for reaching each goal along with required team interactions (individual, sequential, reciprocal, simultaneous)



6. Milestones and Expectations (Define major activities and time frames; discuss team member work styles. Define all expectations, such as "ground rules", and decision-making processes, etc.)

Year 1: As a team-effort, we will make progress on items (a, b) in sub-goal 1, items (a, b) in sub-goal 2, and items (a, b) in sub-goal 3. We held the first part of our (virtual) kick-off meeting in April 17, 2020, and the second part will be held during June, 2020, (virtual again) for finalizing our team-charter. We will plan to meet in December 2020 to discuss how much of our expectations have been achieved.

Year 2: After our 2nd team-meeting in December 2020, we will revisit achievements with respect to milestones, and revise some of the items of each goal if necessary. We would normally hope to complete items (a, b) in each sub-goal. We will plan to hold our team meeting in either California or New Jersey.

Year 3: We will make progress focusing on item (c) in sub-goal 1, items (c, d) in sub-goal 2 and items (c, d) in sub-goal 3. Additionally we will revise milestones based on revisiting them in the team meetings.

Year 4: We will complete remaining parts of milestones from year 3. In the team meeting, we will again revisit achievements versus milestones, and perform item (d) in sub-goal 1, (e, f) in sub-goal 2. We will prepare our deliverable items.

8. Collaboration matrix

Science goals	**Action Team 1** (Global and localized flows) Wang, Braun, Komm, Upton, Liu	**Action Team 2** (Modeling and assimilation) Featherstone, Dikpati, Upton, Liu	**Action Team 3** (Simulations and predictions) Upton, Liu, Dikpati, Wang
1. Develop a consensus set of observational constraints of surface and interior flows, including hemispheric and latitudinal dependence.	Derive global flow measurements (meridional circulation, differential rotation, and large scale convection) from long-term data (1st, 2nd yr) Compare measured localized flows in and around activity-belts (1st & 2nd yr) Develop a consensus set of measured global and localized flows (4th yr)	Take input from sub-goal 1 product, assimilate into models to test predictive capability for time and locations of active region eruption (3rd, 4th yr) Generate a set of global MHD convection-zone models that extend close enough to the photosphere to be compared with and constrained by ongoing local helioseismic observations (4th year)	Estimate how the localized flows in and around active regions may modify the global meridional circulation (1st year)
2. Model global magnetic activity and flows of the solar interior and assimilate observations into those models	Provide consensus measured flows for use in models for performing actions in sub-goals 2 and 3 (3rd and 4th year) Validate modeling from the observations, such as migration of polarity inversion and migration of polar crown filaments From multiple cycle observations to provide clues of similarity between cycle 25 and one of previous cycles.	Simulate evolution of spot-producing fields; generate “imprints” of flux emergence locations and timing from tachocline MHD model-output Perform reciprocative researches on MHD of tachocline model and 3D convection zone dynamics (throughout the project) Giant cell simulations?	Take input from sub-goal 2 and run SFT models using “synthetic” (model-generated) active regions emergence and compare with observations (3rd and 4th year) Compare model-outputs from 3D models averaged over longitudes to SFT model-outputs and find out what we can learn from differences, expecting there would be some but not a lot of differences (3rd and 4th year)
3. Simulate active latitudes and longitudes during the next solar cycle and predict the magnitude and timing of the next solar maximum		Provide simulated magnetic flux distributions (latitude-longitude, size and strength) and timing for using as input “active regions” in performing sub-goal 3 for predicting cycle 25 features (4th year)	Simulate evolution of polar fields from surface flux-transport models (1st & 2nd year) Run SFT models using observed active regions and compare with observations (3rd and 4th year) Run SFT models in data-driven regimes, simulate polar fields, active latitudes and longitudes, and cycle 25 strength (4th yr)

All team members:

1. Dipankar Banerjee (Aryabhatta Research Institute of Observational Science (ARIES)

2. Manora Peak, Nainital-263001, Uttarakhand, India)

3. Doug Braun **(**NorthWest Research Associates, 3380 Mitchell Lane, Boulder, CO 80301-2245, USA

4. Ben Brown (University of Colorado Boulder, 3100 Marine Street, Bldg RL3 Suite A-122, Boulder, CO 80303-1058)

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6. Marc De Rosa (Lockheed Martin Solar and Astrophysics Laboratory, 3176 Porter Dr, Palo Alto, CA 94304, USA)

7. Mausumi Dikpati, (High Altitude Observatory, NCAR, 3080 Center Green Dr., Boulder, CO 80301, USA)

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30. Junwei Zhao (Stanford University, Stanford, CA 94305, USA)