From Active Region to Polar Field: Understanding Solar Cycle Magnetic Evolution with Measured Near-Surface Flows

ABSTRACT

Understanding the solar cycle is a fundamental and important scientific goal central to NASA’s Heliophysics Division. Activity cycles differ substantially from one to another in various ways: the magnitude of solar activity, the timing of polar field reversal, and the asymmetry of magnetic properties in the northern and southern hemispheres. These observed properties are the result of (sometimes subtle) interactions between magnetic fields and flows throughout each sunspot cycle, but are important to understand in order to better address questions of solar cycle activity and to improve cycle predictions.

The proposed research is based on our recent studies that revealed relationships between variation of the poleward motion of photospheric magnetic field regions and properties of magnetic field in solar active regions and surges (Zhao et al. 2014; Sun et al. 2015). The proposal includes tasks of (1) improving the measurement of the temporal and spatial variability of near-surface meridional flows throughout Cycle 24, and in particular better characterizing the poleward motion of photospheric magnetic field regions of different polarities (Zhao et al. 2014) in surges and characteristics of solar active regions (ARs) that are found to be related to variations of meridional flow (Sun et al. 2015); and (2) incorporation, for the first time, of this observation-inferred, temporally and spatially dependent meridional flow within a surface flux transport model (Schrijver & DeRosa 2003), to understand buildup and development of polar fields and to assess the effects of these empirical flow profiles on the evolution of emerging magnetic flux and the resulting sunspot-cycle activity properties.

Helioseismology techniques will be used to measure the temporal near-surface meridional flow profiles during the sunspot cycle. These flow profiles will then be parameterized based on their dependence on polarity and magnetic strength for input into the surface-flux model. We expect to be able to ascertain the contribution of each emerged active region to the decay and re-establishment of the new polar field for Cycles 23 and 24, and to develop a framework through which we can better predict the contribution of emergent active region flux to the decay and re-establishment of polar fields.

The proposed work uses data from current and historical NASA spacecrafts, SDO and SOHO, together with numerical modeling, to establish the linkages of flows, polar field, and solar active regions, and to forecast solar cycles. This is highly related to one of the high level science goals from the Heliophysics Decadal Survey: Determine the origins of the Sun’s activity and predict the variations in the space environment.
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From Active Region to Polar Field: Understanding Solar Cycle Magnetic Evolution with Measured Near-Surface Flows

1. Objectives and Significance

1.1. Overview

Understanding the solar cycle is a fundamental and important scientific goal central to NASA’s Heliophysics Division. Activity cycles differ substantially from one to another in various ways: the magnitude of solar activity, the timing of polar field reversal, and the asymmetry of magnetic properties in the northern and southern hemispheres. A good correlation has been observed between the maximum polar field at the end of one cycle and the magnitude (maximum sunspot number) of next cycle (e.g. Svalgaard et al., 2005), and the correlation is even stronger when consider two hemispheres separately (Munoz Jaramillo et al., 2013). This suggests that the polar field may be a precursor to subsequent sunspot cycle lengths and strengths. Understanding buildup and development of the polar fields is thus the key to advance our knowledge on solar cycle variability.

![Fig. 1.— Magnetic field evolution. Top: Time-latitude diagram of zonally averaged $B_r$, determined from measurements of the line-of-sight magnetic field obtained by HMI. Contours show polarity inversion lines; their intersections with horizontal dotted lines indicate reversals at 60° (star symbols). $N_1$ - $N_5$ and $S_1$ - $S_4$ mark individual flux surges that migrate poleward from the active latitudes. Bottom: Average polar field strength in the northern and southern latitude bands from 60° - pole (From Sun et al. 2015).](image-url)
Fig. 2.— Sunspot butterfly diagram constructed from the DPD catalog (Győri et al. 2011) overplotted on zonally averaged $B_r$. Magnetic data before May 2010 are from MDI. Each circle represents a NOAA AR; ARs with umbrae smaller than 10 µHem are not shown. The symbol size is proportional to the maximum sunspot area within ±30° of central meridian. The color indicates a pooled field proxy for individual ARs, $P \propto \Phi d \sin \alpha \propto d^{2.3} \sin \alpha$, where $d$ is the polarity separation, $\Phi$ is magnetic flux, and $\alpha$ the tilt, given $\Phi \propto d^{1.3}$ (Wang & Sheeley 1989). In the north, ARs with normal tilt for this cycle are blue; inverse tilt red. For south it is the opposite. A blue symbol is expected to contribute positive flux to a surge. Ovals enclose the ARs whose fluxes evolved to form surges $N_1$ (left oval) and $N_2$ (right oval). (From Sun et al. 2015).

Observations have demonstrated that active regions (ARs) are the predominant source of the large-scale polar field (e.g. Sun et al. 2015). Fig. 1 shows the time-latitude diagram of zonally averaged radial field $B_r$ (top panel) and temporal profiles of magnetic field in northern and southern polar caps (bottom panel). In the northern pole, for example, the magnetic field decreases to half of its value in the 6 months from September 2010 to March 2011; then it remains unchanged for the next 6 months (the orange curve in the bottom panel). The decrease of the field is attributed to the arrival of a surge of positive flux marked as $N_1$ in the top panel; whereas the surge $N_2$ of negative flux prevents the field from further declining, maintaining a roughly constant polar field for about 6 months. The source of surge $N_1$ is likely to be several ARs at higher latitude, in north 20°–30°, denoted by an oval at the top left of Fig. 2. These ARs have typical tilt angles that obey Joy’s law. Some following-polarity flux from those ARs is transported poleward, forming this positive field surge. The primary source of surge $N_2$ is probably several ARs observed in the northern hemisphere in early 2011 (denoted in Fig. 2 by the oval at the right). These ARs have tilt angles less than
that expected according to Joy’s law. During a time of weak solar activity, the unusual orientation of these spots resulted in the creation of leading-polarity surge $N_2$; $N_2$ later interrupted the reversal of the northern polar cap. *We believe that if our hypothesis is correct the creation and behaviour of this surge could have been predicted from the characteristics of the emerged regions using the results of our proposed study.*

The poleward motions of the surges of flux shown above are driven mainly by meridional flow. Thus measuring meridional flow is a first step toward understanding and modeling the contribution of an AR to the polar field and solar cycle activity. The flow is found to be modulated by the inflow around ARs, revealed by helioseismic studies (e.g. Zhao & Kosovichev 2004; Gizon 2004; González Hernández et al. 2010). Fig. 3 shows residual poleward meridional flow after subtraction of the mean meridional-flow profiles. Contours of the unsigned total magnetic field obtained by averaging over all longitudes for each Carrington rotation are overplotted. Inflow toward the activity belt is readily seen: it migrates towards the equator as the location of emerging ARs trends toward lower latitude with the progress of solar cycle from minimum to maximum. This inflow helps prevent ARs from dispersal. Fig. 4 displays details of the inflow in one AR. Residual flows in this recurrent region, AR 11106 in Carrington rotation CR 2101 (top left) and AR 11112 in next rotation CR 2102 (bottom left), move convergently in both the east-west (middle) and north-south (right) directions. The inflow persists for these two rotations.
Not only are perturbations of the meridional flow found in ARs, they are also detected in surge areas poleward of the active belts. Combining subsurface flow and magnetic field data has revealed a previously unknown link between the poleward motion of photospheric magnetic field regions of different polarities and variations from the usual solar meridional flow (Zhao et al. 2014). Zhao et al (2014) found that the variation of meridional flow correlates with the magnetic field polarity: areas dominated by trailing field move toward the pole more slowly than the plasma in leading field regions. Combining those various effects will lead to a spatially and temporally dependent meridional flow.

Phenomenological models of magnetic flux transport applied to observed eruptions of photospheric magnetic flux (e.g., DeVore et al. 1984; Wang et al. 1989; van Ballegooijen et al. 1998; Schrijver & Title 2001) have successfully reproduced large-scale magnetic characteristics of the 11-year solar cycle, polar field reversal and butterfly pattern, thus demonstrating a basic explanation of the causes of these fundamental features. While these models incorporate well-established characteristics of differential rotation, meridional flow, and magnetic diffusion, some of the values are determined in an empirical way or trial-and-error manner. For example, the meridional flow is often implemented in the models with little or no temporal dependence and no longitudinal dependence. This leaves substantial room for the models to improve as new meridional flow observations become available. The new meridional flow we propose to derive will be a spatially and temporally dependent flow that includes the newly discovered relationship between the poleward motion of photospheric magnetic field regions of different polarities (Zhao et al. 2014) in surges and characteristics of solar active regions (ARs) that is found in our recent work to be related to variations of meridional flow (Sun et al. 2015).

Inclusion of these two new effects in magnetic flux transport models has potential to improve the results. Tests with a spatially and temporally dependent meridional flow have shown impacts on the model.
results: Previous studies have indicated that the variation in meridional flow is likely to have a significant effect on the buildup of polar fields from cycle to cycle (e.g., Wang et al. 2002) and in each cycle (Cameron & Schüssler 2012). Specifying flows in ARs in the models also showed improvement of the results. For example, parameterized inflows around ARs have been incorporated in some surface flux transport models (Jiang et al. 2010; Cameron & Schüsseler 2012), and investigators find that this does modulate the strength of the polar field and that it can lead to a better correlation between polar field flux and maximum sunspot number in next cycle. However, the inflow parameterized in the model is much stronger than observations (Upton & Hathaway 2014), and this leads to a poorer correlation with the observations (Yeates 2014).

High spatial- and temporal-resolution full-disk measurements of Doppler velocity and magnetic field from SOHO/MDI (Scherrer et al. 1995) and SDO/HMI (Scherrer et al. 2012; Schou et al. 2012) provide an opportunity for us to take a fresh look at the persistent questions of solar cycle activity, with important new data of the near-subsurface flows determined from helioseismic techniques. We propose to improve the surface flux transport model by incorporating the observation-inferred, time- and location-dependent meridional flow data that includes variations in both surge and AR areas, as shown in our recent studies (Zhao et al. 2014; Sun et al. 2015). Meridional flow will be measured using helioseismology techniques (Zhao et al. 2014). Variation of meridional flow will be estimated and empirically formulated based on the relationship of flows and the characteristics of the magnetic field, as shown in Sun et al. (2015). Even though the total flux in the polar fields at sunspot minimum is about the same as that in a large AR and even though the process for tying the polar field to the next cycle is not well understood, the present state of the art in cycle predictions shows that the polar field strength at minimum is a good predictor of the following cycle (See, e.g., Svalgaard et al., 2005). This fact will be used in this study which will endeavor to produce better predictions of the cycle evolution of the polar flux. The ultimate goal is to use new data in a more complete model to address questions of solar cycle activity and to make cycle predictions. The tasks we propose will lead to a better understanding of impact of solar active regions on (1) polar field reversal timing; (2) solar activity cycle amplitude; and (3) north-south magnetic activity asymmetry.

As a demonstration of the potential impact of meridional flow variability on surface flux evolution, Fig. 5 shows the results of three new simulations of the magnetic field using our surface flux transport model (Schrijver 2001; Schrijver & DeRosa 2003). The three cases are the same except for parameterized amplitude variations of meridional flow that vary during the cycle. The standard meridional flow speed, shown in Case A, is based on the mean observed solar profile described in Komm et al. (1993). This orthographic projection shows a synthetic field map near cycle maximum. Cases B was run with a meridional flow multiplier that varied between 1 at minimum and 2 at maximum, whereas Case C has a multiplier varying between 2 at minimum and 1 at maximum, respectively. The north pole is tilted toward the viewer by 40 degrees, so that both polar and equatorial regions are visible. Even with these apparently simple changes to the meridional flow profile, the differences in the resulting surface-flux models are quite noticeable. The polar field flux (shown in Fig. 6) and in particular the surges from the activity belts differ substantially between the three cases. In the proposed project, the addition of a more realistic, time-evolving meridional flow profile will enable us to investigate the detailed buildup of the polar caps and determine the contribution of each newly emerged AR to the breakdown and buildup of the polar caps from cycle to cycle.
Fig. 5.— Snapshots of solar magnetic fields from our surface-flux transport model (Schrijver 2001; Schrijver & DeRosa 2003) for several test runs. There are three cases, each sampled a few years into a sunspot cycle during the run-up to cycle maximum. Case A is a baseline solar case that includes a time-invariant meridional flow profile. Case B shows the effect of increasing the meridional flow during the cycle from the baseline rate at minimum to double that rate at maximum. In Case C, the meridional flow decreases from twice the baseline rate at minimum to the baseline rate at maximum. In these renderings, the north pole is tilted toward the viewer by 40 degrees. The configuration of the high-latitude field clearly depends closely on the meridional flow.

![Snapshots of solar magnetic fields from our surface-flux transport model.](image)

Fig. 6.— Net polar flux north of 60 degrees as a function of time for flux-transport model Cases A (blue), B (green), and C (red) of Fig. 5. Flow rate had a significant impact on the polar field strength from one cycle to the next.

![Net polar flux north of 60 degrees.](image)

1.2. Objectives and Significance

This investigation links comprehensive observations of the emerging solar magnetic field and detailed new knowledge of variations in meridional flow to the development and reversal of the Sun’s polar field, the evolution of large-scale magnetic field patterns, and to hemispheric asymmetry. The strength of the polar field is one important piece of data used to predict the strength of the next solar cycle. The augmented
surface flux transport model will allow earlier and more accurate prediction of the polar field strength and will provide early insight into how ARs that emerge throughout the cycle contribute to the evolution of the large-scale field, including the poles. The large-scale field also determines the magnetic structure of the corona and the heliosphere beyond. While the link between the solar dynamo and large-scale flux transport toward the poles and across the equator is not fully understood, its importance is very clear, as is the relevance to the stated goals of NASA’s Heliophysics program. The approach and methodology described in the next sections provide a clear path forward that will take effort to achieve, but the required magnetic and velocity observations are available, the team has demonstrated experience with the HMI and MDI data and analysis and with the models to be employed, and the investigation faces no technological barriers that would threaten completion.

2. Scientific Goals and Technical Approach

We propose to investigate the coupling between the individual ARs that emerge onto the solar photosphere and their effect on the subsequent evolution of the polar fields. Most properties of polar flux evolution, such as the timings of reversals, the magnitudes of newly formed polar caps, and asymmetries between the northern and southern hemispheres, are known to be affected by the many factors, including the number and latitude of emergent ARs, their Joy’s Law tilts, and the meridional flows that advect this flux poleward. With the availability of long-term, well calibrated surface-flow data inferred from SOHO/MDI and SDO/HMI data, we are now in a position to determine the effects of time-varying meridional flows on observed ARs throughout sunspot cycles 23 and 24. In particular, we will be able to characterize the contribution of each AR to the build up of polar caps throughout each sunspot cycle.

This project consists of implementing a time- and spatially-dependent meridional flow into an evolving surface flux transport (SFT) model of photospheric magnetism. Earlier studies have typically focused on zonally averaged, long-term properties of surface-flux evolution. By including a more detailed treatment of the meridional flows, to which the poleward transport of flux is particularly sensitive, we will be able to better establish the contribution of each AR to longer-term trends such as the buildup of flux in each polar region. Because SFT models are two-dimensional, they run fast and thus we will be able to assess the resulting polar flux evolution by statistically sampling an ensemble of such models.

This project involves two main parts, parameterizing a time- and spatial-dependent meridional flow (Section 2.1) and exploring the relationship between ARs and solar cycle properties (Section 2.2). In Section 3, we present the detailed methodologies and corresponding work plans to address these goals.

2.1. Parameterizing a Time-dependent Meridional Flow Profile

Discussions in the previous section suggest that the meridional flow profile $F(t, \theta, \phi)$ consists of two components: a slowly varying background $f_{bg}$, and a magnetically dependent, local variability $f_{mag}$:

$$F(t, \theta, \phi) = f_{bg}(t, \theta) + f_{mag}(t, \theta, \phi),$$  \hspace{1cm} (1)
where $\theta$ and $\phi$ refer to latitude and longitude, respectively. Here, $f_{bg}$ represents the standard background flow that depends on cycle phase ($t$) and latitude ($\theta$) only. The new term $f_{mag}$ represents the component that gives rise to the observed correlations between the meridional flow speed and magnetic field, i.e. ARs and surges. This component varies on AR evolution time scale, and is longitudinally resolved (Fig. 4). These components will be empirically formulated by observation-based results (see Section 3.1).

2.2. Exploring the Relationship Between Active Region and Solar Cycle Properties

Our SFT model will be employed to study the impact of ARs on the polar field evolution, and to develop a prediction scheme for solar cycle magnitude. This SFT model will contain our more realistic meridional flow, together with a field-strength dependent diffusion coefficient (Schrijver & DeRosa 2003).

The effect of the new meridional flow profile will be tested using observation-based AR sources (Section 3.2.1). Further, ARs with various properties of flux, tilt angle, and separation, in the form of both idealized bipole sources and observed magnetograms, will be used as input to the SFT model; the modeling result will be analyzed to quantify their contributions to the polar field (Section 3.2.2). New and archival magnetograms will be utilized, together with an ensemble modeling technique, in an attempt to develop a prediction scheme of the upcoming solar cycle magnitude that accounts for the randomness of the toroidal-poloidal field conversion in the Babcock-Leighton mechanism (Section 3.2.3).

3. Methodology

3.1. Meridional Flow From Observation

We will use time-distance helioseismology to infer the flow on the solar surface. Time-distance helioseismology is a local-helioseismology technique to infer the Sun’s local-scale subsurface flow field and structure. Basically, time-distance helioseismology measures acoustic travel time between two locations, say $A$ and $B$, on the surface by cross-correlating the oscillation signals observed at these two locations. The acoustic waves travel along a curved path through the solar interior, hence carrying the interior information back to the surface. Technically, one is able to measure the travel times from $A$ to $B$ and from $B$ to $A$. Approximately, the mean of these two travel times corresponds to the interior structures, and the differences of these two are affected by the interior flow field. Subsurface flows are inferred from an inversion process using the measured travel times and sensitivity kernels developed from a model and consistent with the travel time fitting methods.

The data to be used are MDI data from 1995 to 2010 and HMI data from 2010 to 2015 (and beyond). Actually, a time-distance data-analysis pipeline has been developed for HMI observations, and routine analysis is carried out on a daily basis (Zhao et al. 2012). The flow velocities to be used in this study are standard products of the HMI helioseismology pipeline and these products are available on-line to all. Those data and data products will be used to infer the meridional flow $F(t, \theta, \phi)$, as presented in Eq.1.
3.1.1. Background Meridional Flow

We propose two schemes to parameterize the background, slowly varying flow $f_{bg}(t, \theta)$ in Eq. 1, which may be cross-checked each other.

**Averaging quiet-sun regions.** A straightforward test is to remove the ARs and their surroundings (20-30 degrees; see Fig. 4) in the meridional flow maps, and perform zonal averages of the rest. We can determine the AR location using the SHARP (Spaceweather HMI Active Region Patches; Bobra et al. 2014) data product from HMI. This method should work better during the minimum phase. Removal will be difficult during the maximum phase, as most of the low latitude regions will be occupied by ARs.

**Joint function fitting with AR inflow.** The alternative assumes that the dependence on latitude is un-changing, that is,

$$f_{bg}(t, \theta) = c(t)f_0(\theta),$$

and assumes some analytical form of $f_0(\theta)$, for example, the Legendre polynomial $P(\theta)$. The observed flow maps will be zonally averaged and smoothed in time. The term $f_{bg}$ and the zonally averaged term $f_{mag}$ (see below, averaged over $\phi$) will be fit together to the observed, zonally averaged profile ($t$ and $\theta$ dependent). Operationally, because the flow profile evolves slowly in time, this fit will be performed a few times a year to include the new information as the cycle progresses.

3.1.2. Magnetic-Dependent, Local Flow Variability

The new local variability term $f_{mag}(t, \theta, \phi)$ in Eq. 1 depends on the detailed distribution of the magnetic field. Zhao et al. (2014) have shown that the local velocity variability is anti-correlated with the surge field, $B^*$. Sun et al. (2015) demonstrated that this component is anti-correlated with the AR magnetic flux $\Phi$ (see Figs. 4 and 7). Further, the surge field $B^*$ itself is correlated with AR properties, e.g. tilt angle $\lambda$ (Fig. 8) and perhaps polarity separation $d$. We can write:

$$f_{mag}(t, \theta, \phi) = f_{mag}(\Phi, \lambda, d, B^*),$$
where $\Phi$, $\lambda$, $d$ and $B^*$ are functions of $t$, $\theta$, and $\phi$. We propose to better formulate this term using the following approach.

**Fitting the flux-dependency.** A $\Phi$-dependent AR inflow (Zhao et al. 2004, Gizon et al. 2004) has been employed and parameterized (Cameron et al. 2012) to explain the local meridional flow variability. Here, we will construct a 2D function to account for the longitudinally localized AR inflow (see Fig. 4). A $\Phi$-dependent AR inflow will be determined based on flow and magnetic field data in ARs (see Fig. 7). The sample ARs are readily identified and extracted by the SHARP data product.

**Searching for dependence on other parameters.** There may be a mechanism by which the individual AR properties like $\lambda$ and $d$, or an individual surge with field $B^*$ can change the local meridional flow. Preliminary inspection suggests that ARs with similar flux but opposite-signed tilt do not induce inflow of significantly different magnitude. Fig. 8 shows correlations between tilt angle of ARs and field strength in surges averaged over each solar rotation (left) and between the residual of meridional flow and field strength
in surges (right). $\Delta \theta$ represents difference of the flux-weighted AR centroid latitude of two polarities, averaging over each rotation, and thus can be served as a proxy of tilt angle $\lambda$. We have speculated that the correlations observed in the zonally averaged values (Zhao et al. 2014; Sun et al. 2015), e.g. between tilt angle and meridional flow (left panels in Fig. 8) are likely the consequence of the surface flux transport process when taking into account Joy’s law and the $\Phi$-dependent AR inflow (Sun et al. 2015), as shown in Fig. 8. Here, we propose to test this idea by performing a survey using the SHARP sample. Values of $\lambda$, $d$ and $B^*$ measured from individual ARs will be correlated against the local meridional flow. If no obvious correlation exists, we obtain a simple profile $f_{\text{mag}} = f_{\text{mag}}(\Phi)$. Otherwise, the surface flux transport paradigm will need to be adjusted – a scenario that can itself be interesting.

### 3.2. Active Regions and Solar Cycle Activity

How properties of ARs impact solar cycle activity is investigated using the aforementioned observation-based parameterised meridional flow $F(t, \theta, \phi)$ and a SFT model. The existing SFT model simulates the evolution of the radial magnetic field $B_r(\theta, \phi, t)$ based on the radial component of the magnetic induction equation, subject to prescriptions for the advection velocity and flux emergence, cancellation, and dispersal (e.g. DeVore et al. 1984; Wang et al. 1989; Schrijver 2001):

$$
\frac{\partial B_r}{\partial t} = -\omega(\theta) \frac{\partial B_r}{\partial \phi} - \frac{1}{R \sin \theta} \frac{\partial}{\partial \theta} \left[ v(\theta) B_r \sin \theta \right] + \frac{\kappa}{R^2} \left[ \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial B_r}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2 B_r}{\partial \phi^2} \right] + S(\theta, \phi, t),
$$

where $\omega(\theta)$ is the differential rotation rate, $v(\theta)$ is the meridional flow, $\kappa$ is the magnetic diffusion coefficient, $R$ is the solar radius, and $S(\theta, \phi, t)$ is a source term that describes the emergence of magnetic field regions. The model used in this research (Schrijver 2001; Schrijver & Title 2001; Schrijver & DeRosa 2003) will be modified to include spatially and temporally varying flows. The model involves injecting bipolar regions ranging from large ARs to small ephemeral regions onto the model solar photosphere, based on observed, time-dependent distributions of latitude, flux, and orientation of emerging flux. Nesting properties of successive generations of bipoles are also included. Time- and location-dependent magnetic diffusion coefficient is also incorporated in the model, which enables the use of a more realistic coefficient, such as a magnetic field strength dependent coefficient, if needed. Examples of simulation results from this model are shown in Figs. 5 – 6.

The model is expected to run in two modes. In one mode, synthetic ARs will be inserted as sources, $S(t, \theta, \phi)$, according to empirical distributions such as Joy’s law. In the other mode, observed magnetograms will be assimilated in time, so our choice of the model parameters mainly controls the far side of the Sun. The main outputs from the model are the mean field and the flux pattern of the surges, and the mean polar field. They will be compared with magnetic observations for evaluation and validation.

### 3.2.1. Effect of a Varying Meridional Flow on SFT Model

Previous SFT modeling with cycle-specific meridional flows is able to recover the cycle magnitude and polar field (Wang et al. 2002). The flow speed is manually tuned, which may differ from observations.
Time-dependent meridional flow from feature tracking has been incorporated into SFT modeling recently (Upton & Hathaway 2014), although there is still difficulty reproducing the weak polar field between Cycles 23 and 24.

Effect of varying background flow. The effect of a constant meridional flow speed (time independent) with a predetermined latitudinal dependence has been systematically explored by Baumann et al. (2004). We aim to explore the effect of the time- and latitude-dependence of the background flow. A set of $f_{bg}(t, \theta)$ profiles will be designed and incorporated to the SFT model. After runs with both artificial source and data assimilation, we will systematically study the impact on the surge and polar field.

Effect of AR inflow. One new feature in our meridional formulation is the explicit, longitude-resolved AR inflow. We plan to design a suite of tests to study its effect on flux transport. Such test may include: cases with or without inflow; with weak or strong inflow; with field-dependent or independent inflow; with longitude-resolved or Carrington Rotation averaged inflow, etc. The resultant surge and polar field will be compared with each other, and further compared with observation.

Cross-checking using ensemble Kalman filter data assimilation. We propose to cross-check our modeled meridional flow by making predictions of the cycle evolution using the Ensemble Kalman filter data assimilation technique (Dikpati et al., 2014). This test builds on established algorithms and can be carried out along with our development of the cycle prediction model (see Section 3.2.3). The predictions will be evaluated as the cycle progresses, as the models with different meridional flow profiles start to differ.

3.2.2. Impact of AR Property on Polar Field Reversal

In the Babcock-Leighton mechanism, ARs manifest the conversion from global toroidal field to poloidal field. The AR emergence is affected by stochastic processes, which generates scatter in the AR properties such as the tilt angle. The flux transport process then redistributes the AR poloidal field to the global scale. With the updated SFT model at hand, we propose to explore how these AR properties affect the polar field evolution, particularly its polarity reversal.

Poloidal field from individual AR complexes. The total poloidal field from ARs has been parameterized and shown to be well correlated with the global dipole (e.g. Petrie 2012). Nevertheless, it is not clear how much each AR complex contributes to the global poloidal field, given the long poleward transport time and the diffusive processes occurring along the way. Yeates et al. (2015) attempted to address this question by excluding AR nests from the SFT model and examining their contribution to the poloidal field. By inserting idealized bipoles into the SFT model, we will determine how temporally and spatially dependent meridional flows affect the contribution of the polar fields from ARs having various properties, such as emerging latitude, total flux, tilt, polarity separation, etc. We will then search for observed ARs with representative properties and assimilate them in the SFT model for comparison; we will also compare observation with SFT models in which specific AR(s) is excluded, as Yeates et al. (2015) did.

Impact of scatter in AR tilt angle on north-south asymmetry. The predictability of cycle magnitude is restricted by the scatter of AR properties (see Section 3.2.3). We have shown that the inversely tilted ARs emerging in the south at the beginning of Cycle 24 delayed the polar field reversal, whereas strong normally-tilted ARs in the north canceled half of the polar flux within one year (Figs 1 & 2; Sun et al. 2015). How
does the scatter in AR tilt contribute to the north-south asymmetry? Jiang et al. (2015) compared the real data and the SFT models using the Joys law determined with observation (Li & Ulrich 2012). The tests show that large outlier ARs will have a significant impact. Using results from the previous task that derives a better meridional flow, especially in ARs, we will quantify the contribution from these particular ARs. The SFT model will then be applied to Cycles 21-23 (We will use Mount Wilson magnetograms for Cycles 21-22, as shown in Li & Ulrich 2012, and MDI magnetograms for Cycle 23), where most of them show north-south asymmetry in polar field reversal. Modeling with data assimilation will help identify the offending ARs and quantify their contributions.

**Impact of large vs. small bipoles.** Past implementation of SFT models with idealized sources have focused on large ARs, those provided by the NOAA list, for example. The smaller bipoles may also contribute to the polar field reversal, especially if their tilt distribution deviates from those of larger ARs (Tlatov et al., 2014). To quantify this, we will perform several tests in which we include only idealized large ARs, or idealized smaller bipoles. We will also systematically mask out the large or small bipoles in the observations and use them for assimilation. The effect on the polar field evolution will be quantified.

### 3.2.3. Towards Prediction of Solar Cycle Magnitude

As mentioned in Section 1, a good correlation has been observed between the maximum polar field at the end of cycle $N$ and the magnitude (maximum sunspot number) of cycle $N + 1$ (e.g. Svalgaard et al., 2005). The cycle magnitude of cycle $N + 1$, on the other hand, is not well correlated with the maximum polar field of the following minimum. This phenomenon, thought to be caused by the stochastic nature of the toroidal-to-poloidal field conversion during AR emergence, renders solar cycle prediction difficult.

We propose to test an ensemble modeling scheme, updated from DeRosa (2005), that aims to predict the maximum polar field of cycle $N$ for each hemisphere, thus the cycle magnitude of cycle $N + 1$. It is likely that the cycle predictability is strongly limited by the minority of ARs flux or tilt that deviates from the statistical distribution (e.g. Joy’s law). An anomalous AR, especially if it is large, can have an outsized effect on the contribution to the polar field (e.g. Jiang et al 2015). By performing a large ensemble of SFT models that incorporates different AR distributions (number, flux, tilt, etc.) and background meridional flows, we may characterize the variability in the polar field evolution by determining the ensemble mean and scatter.

**Framework.** At a certain time $T$ during cycle $N$, we start modeling with an observed magnetic map. We introduce a statistically determined distribution of synthetic AR sources $S(t > T)$ as idealized bipoles. The sources are constrained by the maximum sunspot number as determined from the polar field of cycle $N - 1$, and include in particular the anti-Joy’s AR population whose distribution is determined from observation (e.g. Li & Ulrich, 2012; Jiang et al. 2015). A large number of realizations will be applied. The background meridional flow $f_{bg}$ up to time $T$ has been observed and parameterized. Future values can either be fixed at $f_{bg}(T)$ or scaled from previous cycle observations. This ensemble of models will be run until the polar field reaches maximum at a time $T_m$, when we make an ensemble prediction of cycle $N + 1$. As the cycle progresses, the model will be re-run with new initial condition, better constrained $S$ distribution, and more recent meridional flow $F(t, \theta, \phi)$. The prediction will then be updated.
**Prediction.** The model will match the observations at the time we observe the maximum polar field \( T_m = T \), and be less accurate earlier in the cycle. One way to characterize the effectiveness is the lead time, \( \Delta T = T_m - T \), at which the modeled maximum polar field is close enough to the eventual observation. We will use data from the previous cycles for testing, where the magnetic field is frequently observed, and the meridional flow is either observed or parameterized. The model will be directly applied to the current cycle toward a prediction of Cycle 25.

**Cross-checking meridional flow (from Section 3.2.1).** A recently proposed scheme to estimate the meridional flow variation employs the ensemble Kalman filter (EnKF) algorithm (Dikpati et al., 2014). This scheme assumes an ensemble of meridional flow changes at each time, utilizes a flux transport dynamo model to evaluate the possible magnetic evolution using each flow profile in the ensemble, compares the modeled magnetic field to new observed field, and adjusts flow changes in the ensemble accordingly. We propose to apply a similar scheme, using the SFT model instead of the flux transport dynamo model. The ensemble-mean meridional flow estimates the profile that is required to reproduce the polar field in our SFT model (i.e. it will be self-consistent), and can be used to cross-check our meridional flow parameterization. The EnKF algorithm is readily available in modularized form from UCAR (http://www.image.ucar.edu/DaReS/DART/).

### 3.3. Data and Model Readiness

We will use data from SOHO/MDI and SDO/HMI such as Dopplergrams and magnetograms, and their higher level data products routinely produced at SDO JSOC at Stanford, including subsurface flow maps from time-distance helioseismology and synoptic maps of magnetic field. These data and data products are already available to the community through the JSOC website (http://jsoc.stanford.edu). Data from Mount Wilson Observatory are available on-line at http://obs.astro.ucla.edu/intro.html.

The SFT model used in this proposal is based on the code developed by C. Schrijver and M. L. DeRosa at LMSAL (Schrijver & DeRosa 2003). A newer, grid-based version is being tested under a separate NASA/NSF project (CGEM) for which DeRosa is the LMSAL Institutional PI and in which members of the Stanford Solar Group also participate. The new model is tailored to accept HMI or MDI data as input, and is flexible to utilize idealized bipole sources and various meridional flow profiles.

### 4. Relevance of Investigation to the Heliophysics Program and Broader Impacts of the Proposed Work

The proposed work uses data from current and historical NASA spacecrafts, SDO and SOHO, together with numerical simulations, to establish the linkage between surface flows, the polar field, and magnetic features at the surface, and to forecast solar cycles. This is directly related to one (#1) of the high level science goals from the 2012 Heliophysics Decadal Survey: Determine the origins of the Sun’s activity and predict the variations in the space environment. It directly addresses research focus areas H1, F4, and J2 described in the 2009 Heliosphysics Roadmap. Better knowledge and forecasts of the large-scale magnetic field of the Sun also improve our ability to determine the configuration of the corona and heliosphere.
5. Work Plan, Management, and Personnel Commitments

First year: identify and classify properties of the magnetic field in ARs in the time period beginning May 2010 using HMI observations that cover most of Cycle 24; analyze the near-surface meridional flows derived using helioseismology techniques through the HMI/JSOC pipeline supported by NASA; quantify the relationship between magnetic properties on the photosphere and subsurface flows. Analyze the results of running the SFT model with synthetic ARs and flow characteristics.

Second year: extend the above analysis to Solar Cycle 23 using MDI observations and also derive the meridional flows; measure and quantify meridional flow as a function of time and location; incorporate this information into the SFT model; use Mount Wilson Observatory data of Cycles 21-22 to study impact of scatter in AR tilt angle on north-south asymmetry.

Third year: determine the links between flows, polar field, and active regions; use the quantitative understanding to forecast solar cycle characteristics, e.g. estimate the timing of the polar field reversal, the ultimate strength of the polar field, and the hemispheric asymmetry of magnetic activity; develop a prediction scheme.

PI Y. Liu will be responsible to see that the investigation is accomplished. He will coordinate research efforts of the team. He will analyze observational and simulation results, and parameterize meridional flow that will be used in the SFT model. He will help run the SFT model and study impact of ARs on polar field reversal. He will spend 15% of his time on these proposed tasks.

Co-I P. H. Scherrer will advise Dr. Liu in the overall management and provide scientific insight and discussions, particularly the interpretation of the data from HMI and MDI.

Co-I J. T. Hoeksema will spend 5% of his time on this project. He will analyze observational and simulation results. He will provide his expertise in research and prediction of solar cycle activity, and help develop solar cycle prediction scheme.

Co-I J. Zhao will provide methods to extract the needed flow data from the existing standard data products. He will help derive the time- and spatial-dependent meridional flow. He will spend 10% of his time on this project.

Co-I X. Sun will perform analysis on magnetograms and explore the relationship between flow and magnetic field. He will analyze observational results and derive empirical formulae between flow and magnetic field. He will help run the SFT model and develop the prediction scheme. He will spend 10% of his time on this project.

Co-I M. L. DeRosa at Lockheed Martin Solar and Astrophysics Laboratory (LMSAL) will provide the results of the surface-flux transport model to Stanford Co-Is for comparison, and will provide scientific insight and discussions on observational and simulation results. He will investigate effect of a varying meridional flow on SFT model and help develop solar cycle prediction scheme.
REFERENCES


This preprint was prepared with the AAS LaTeX macros v5.2.