Evolution of the Global Solar Magnetic Field over 4 Solar Cycles: Use of the McIntosh Archive


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Abstract
The McIntosh Archive consists of a set of hand-drawn solar Carrington maps created by Patrick McIntosh from 1964 to 2009. McIntosh used mainly Hα, He-I 10830Å and photospheric magnetic measurements from both ground-based and NASA satellite observations. With these he traced polarity inversion lines (PILs), filaments, sunspots and plage and, later, coronal holes, yielding a unique ~45-year record, over four complete solar cycles, of synoptic maps of features associated with the large-scale organization of the solar magnetic field. We first discuss how these and similar maps have been used in the past to investigate long-term solar variability. Then we describe our work in preserving and digitizing this archive, developing a digital, searchable format, and creating a website and an archival repository at NOAA’s National Centers for Environmental Information (NCEI). Next we show examples of how the data base can be utilized for scientific applications. Finally, we present some preliminary results on the solar-cycle evolution of the solar magnetic field, including the polar field reversal process, the evolution of active longitudes, and the role of differential solar rotation.

1. BACKGROUND

1.1 Science Objectives

The solar magnetic field is constantly changing, driven by the dynamo below and driving in turn a field that permeates the heliosphere. Concentrated magnetic flux is generated in the Sun’s interior and emerges through its surface, where its evolution is manifested in large-scale features like coronal holes (CHs), filaments, polarity boundaries, and active regions and sunspots. Ongoing diffusion and transport by solar-surface flows results in a shifting pattern of positive and negative magnetic polarity that is an evolving boundary on the global magnetic field. Overall, these motions give clues to the internal fluid dynamics of the Sun and its dynamo processes over solar-cycle (SC) time scales.

The Sun reveals at least two characteristic migrations of surface features (see, e.g., Hathaway, 2015). The first is the equatorward movement of sunspots, a key aspect of the 11-yr activity cycle. The second is the poleward movement of high-latitude filaments/prominences and their related unipolar magnetic regions (UMRs), the so-called “rush to the poles”, which is a tracer of the solar polarity reversal process and the onset of the 22-yr magnetic cycle. Zonal flows such as the torsional oscillations have been associated with both of these migrations. Observations of small-scale magnetic features, such as bright points, sunspots and CH centers (McIntosh et al., 2014; 2018), as well as helioseismic studies of the zonal flows (Howe, 2016) provide support for an extended period of solar activity, e.g., from 17-22 years long (Cliver, 2014).

The rush-to-the-poles phenomenon observed in both solar filaments and in coronal emission and the zonal flows may be fundamental to the polarity reversal and the subsequent development of the polar fields (Babcock, 1961; Leighton, 1964; 1969.). The polar field strength at solar minimum, either measured directly or deduced from the number of observed polar faculae, has been used to predict the peak sunspot number of the following cycle (Munoz-Jaramillo et al., 2013). Thus, observations of the evolution of
these features over long, SC-time scales are fundamental for understanding the solar dynamo and its effects at the surface.

The overall science objective which is enabled by the newly processed McIntosh Archive (McA) maps is to investigate long-term solar variability over SC periods. Our analysis work emphasizes understanding the SC variation of the toroidal and poloidal components of the magnetic field, its connection to the dynamo and dynamo models, the sources and evolution of active regions, CHs, filaments, and how the rotation rates of the various solar features vary over these cycles.

1.2 History and Preservation

To pursue such studies, Patrick McIntosh in 1964 (SC 20) began creating hand-drawn synoptic maps of solar activity, based on daily Hα imaging measurements (Figure 1, top). These synoptic maps were unique because they traced the polarity inversion lines (PILs) connecting widely separated filaments, fibril patterns and corridors within active areas to reveal the large-scale organization of the solar magnetic field. At the time, magnetographs were expensive and the resultant magnetograms not routinely available. Another advantage of Hα measurements was that PILs could be more precisely determined in weak field regions and near the poles of the Sun (Fox et al., 1998; McIntosh, 2003). It has been shown that the large-scale Hα patterns on the surface match well the large-scale magnetic fields measured with magnetograms (e.g., McIntosh, 1979).

CHs were added to the maps, routinely starting in 1981, primarily using ground-based He-I 10830Å images from NSO-Kitt Peak. Magnetograms were used, when available, to determine the overall dominant polarity and to show where the polarities changed. Some of the original hand-drawn McIntosh maps were published as Upper Atmosphere Geophysics (UAG) reports in McIntosh (1975), McIntosh and Nolte (1975), and McIntosh (1979). Versions of the maps were also routinely published in the Solar-Geophysical Data (SGD) Bulletins (the “Yellow books”) in the Prompt monthly reports, and all of these reports are archived at the NOAA National Center for Environmental Information (NCEI).

McIntosh and his assistants created these synoptic maps for each Carrington Rotation (CR) during the interval 1964-2009, with some gaps including a 2-year period from July 1974-July 1976. This 45-year period covers four complete SCs, or 600 CRs. The features on the maps include filaments, large-scale positive and negative polarity regions, CHs of each polarity, sunspots and active regions (Figure 1, top). The McIntosh map collection is unique, providing a consistent view of the evolution of the global solar field.

Although Pat McIntosh is now deceased (Hewins et al., 2017), Ian Hewins and Robert McFadden were trained in the mapping by Pat from 2000-2010. However, many of the maps and other related materials only existed in hard-copy format in boxes and were scattered in various homes and basements. In addition, none of the scanned maps possessed metadata allowing digital searches and analyses. The first and foremost intent of the McA project was to preserve the archive in its entirety. This has been achieved by collecting and collating all of the material at the High Altitude Observatory (HAO) in Boulder, CO and completing the scanning of all of the maps in a uniform manner.

Scientists in France (Meudon Observatory), Russia, India and China attempted to create similar maps in the 1970s and 1980s. However, those efforts were short-lived or limited to filament patterns, making the McIntosh collection of maps a unique and consistent set of global solar magnetic field data for SCs 20-23. Also available at HAO is an original atlas of 132 Hα synoptic charts for SC 19 (1955-1964) that were produced by V. Makarov and K. Sivaraman from Kodaikanal (India) Solar Observatory (KSO) Hα filtergrams and CaK spectrophotograms and other data sources. The SC 19 charts were published in Makarov and Sivaraman (1986). The procedures they used for producing the SC 19 maps, especially for
inferring magnetic polarities and PILs, are documented in that bulletin and two earlier papers - Makarov et al. (1983) and Makarov and Sivaraman (1983) - and closely follow those of McIntosh (e.g., 1972; 1979). Although the KSO SC 19 charts do not show active regions, plage, sunspots or CHs, the reliability and accuracy of the neutral lines and inferred magnetic polarities and their boundaries appear to be consistent with the McA maps. Recently the archive of white light, Ca K and Hα image data at KSO extending back to about 1912 has been digitized and calibrated, and some results published (e.g., Chatterjee et al., 2016; Mandal, Chatterjee and Dipankar, 2016; Mandal et al., 2016; Mandal and Banerjee, 2016; K. Tlatova and A. Tlatov, 1917, private communication).

1.3 Previous Studies Using the Original McIntosh Maps

A variety of historic scientific discoveries have depended on the use of the McIntosh synoptic maps (see McIntosh, 2003, for a review). For example, the maps have been used to describe the drift of polar crown filaments (PCFs) to higher and lower latitudes, the disappearance and reappearance of polar CHs, and the reversal of the polar magnetic field (e.g., Webb et al., 1978; 1984). Figure 2 shows for SC 20-22 the location of the maximum latitude for the PCFs as traced on these synoptic maps, including the “secondary” PCF that appears at lower latitudes and replaces the “true” PCF after the solar magnetic field reverses. The PCFs and their PILs trace the final boundary between the old-cycle polarity, which will reverse at cycle maximum, and the new-cycle polarity which replaces it, an evolution that takes about 15 years (McIntosh, 1992). These motions and their evolution provide important clues about the fluid dynamics of the Sun and its dynamo processes. More recently, McIntosh’s maps have also been used to study the morphology and global context of coronal cavities, as part of a study of the nature of coronal mass ejection magnetic precursors (Gibson et al., 2010), and the global context of solar activity during the last solar minimum (Thompson et al., 2011; Webb et al., 2011).

The Hα synoptic maps have proven to be a unique tool for studying the structure and evolution of the large-scale solar fields and polarity boundaries, because: (1) they have excellent spatial resolution for defining polarity boundaries, (2) the organization of the fields into long-lived, coherent features is clear, and (3) the data are relatively homogeneous back to the start of cycle 20 in 1964 (McIntosh and Wilson, 1985). Time-series zonal “stack plots” of the maps are invaluable in identifying and tracking large-scale features, including polarity boundaries, CHs and active longitudes, over SC time scales (e.g., McIntosh 2003; Gibson et al., 2017). Figure 3a shows a black and white figure P. McIntosh used to display the large-scale polarity patterns for high solar latitudes for 1964-1967 comparing the north (left) and south (right) poleward zones. The barber-pole patterns denote the varying rotation rates of the long-lived, large-scale patterns. An atlas of stack plots of the Hα synoptic charts covering two full SCs, from 1966-1987, was published by NOAA (McIntosh et al., 1991). Decadal stack plots have demonstrated the evolution of gaps in the polar crown, polarity reversals and longitudinal pattern drifts that circle the Sun over a cycle (McIntosh and Wilson, 1985; McIntosh, 2003). Their analysis led to the development of a model of flux emergence and surface evolution (McIntosh and Wilson, 1985; Wilson and McIntosh, 1991).

As we have progressed in archiving and digitizing the McIntosh archive, we have made it available online as described below. Already groups around the world have started to use it in scientific analyses, e.g., Mazumder et al. (2018); Gibson et al. (2017).

2. DATA FORMAT AND PROCESSING DETAILS

2.1. Summary of Method

With NSF support, the original data have been preserved and organized by scanning and digitally processing the maps into a consistent, machine-readable format. The result is an archive, which we call
the McIntosh Archive (McA) that may be utilized by scientists and the public for years to come. This work has been performed at Boston College and the NCAR/High Altitude Observatory (HAO) in Boulder, CO. A website describing and providing access to the archive can be found at: https://www2.hao.ucar.edu/mcintosh-archive/four-cycles-solar-synoptic-maps.

The maps are preserved in three formats:

- Level0 GIF images are direct scans of the original hand-drawn McIntosh maps.
- Level1 GIF images have been cropped, oriented and scaled for consistency, as described below.
- Level3 FITS format files and associated GIF images represent the fully processed maps, as described below.

The processing consists of using Photoshop and IDL to convert the maps to a standard size based on number of pixels in width (heliolongitude) and height (heliolatitude), to remove any unnecessary notes, marks, or symbols, and to colorize the maps. The final Level3 maps key on PILs, or “neutral” lines, which form the boundary between opposite-polarity photospheric magnetic fields. Solar features included on the maps are: CHs having positive-polarity magnetic field and their boundaries, positive magnetic fields, CHs having negative-polarity magnetic field and their boundaries, negative magnetic fields, PILs, filaments, sunspots, and plage groups. The final archive maps have these features identified by ten IDL colors (numbers) which permit digital sorting for data analysis purposes. In addition, missing data is identified in yellow (usually in the polar regions above 70°).

We have written an IDL code, plotfinal.pro that makes plots from input Level3 files FITS files for McA maps for a given CR number (e.g., Figure 1, bottom). We are also writing other codes to permit efficient searches of the map arrays. These codes are publicly available with the processed maps archived at the NOAA's National Centers for Environmental Information (NCEI) in their final, searchable form at: https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-imagery/composites/synoptic-maps/mcintosh/ (and accessible through the above HAO online site).

For a given CR, plotfinal.pro can produce up to 16 permutations of the (FITS) mapping variables that are output as “final” GIF files depending upon keyword settings. These are 8 with a heliographic grid and annotations and 8 with no grid and annotations. Other combinations include extensions of +/-30° for -30° to 390° in solar longitude, or only 0°-360° in solar longitude; missing yellow data poleward of +/-70° in solar latitude, or missing yellow with only CH boundaries, or CHs filled in with missing yellow negative or positive polarity, or all colors filled in near the poles. The final file names reflect these combinations. Since all the final CR maps have the same color system and known scaling, features can be intercompared over many CRs, with time and as a function of solar cycle.

A metadata spreadsheet is maintained for all processed maps and contains information such as data sources and cartographic notes, and is also available through the online sites. For each CR map the spreadsheet contains information about the McA data sources, the individual(s) responsible for map creation, and comments. The data types include filaments and other tracers of PILs, photospheric magnetic field polarities, CH boundaries, sunspots and plage. The data sources vary with time and include ground-based telescopes at various solar observatories, including NOAA-Boulder, Big Bear Solar Observatory (BBSO), Meudon, National Solar Observatory (NSO), He-I 10830Å (NSO), SOON and ISOON, Mauna Loa Solar Observatory (MLSO), GONG, He-I SOLIS, He-IIÅ 304Å and MDI images on the SOHO spacecraft, etc.

2.2 Current Status of the McA

When completed the McA CR maps will permit measurements of the evolution of the large-scale, global magnetic field of the Sun over the course of four solar cycles. However, there are incomplete or missing maps during this period that need to be completed using original data sources. The archive for SC 23,
from 1996 into 2009, is complete (e.g., Gibson et al., 2017), as is the entire period between the maxima of SCs 21 and 22. The scanning of all of the original maps, 1964-2009, to Level1 has been completed. As of this writing we have brought all the original maps that we consider were completed to the final Level 3. Presently 3/4 of the 600 possible CR maps have been completed as Level3, starting in SC 20 in 1966 through to the start of SC 24 in 2009, but with gaps in SCs 20, 21 and 22. Here we are presenting scientific results based on a complete processing of all the original maps that we consider completed.

2.3 Future Processing Work

Our processing goal is to complete the incomplete or missing maps so that the McA will provide a continuous record of solar surface structures over four SCs for the community. The remaining processing tasks include bringing the remaining original McIntosh maps to Level3, and completing or creating the ~130 CR maps that are incomplete or missing from the original archive. As part of this processing, we are adding CHs to the maps when sufficient CH observations are available. Most of these CHs are from He-I 10840Å observations when these images became available in April 1974 with CR 1614. To date we have added He-I 10840Å CHs to most of the otherwise complete maps between 1974 and 1981. In addition, we added CHs for 8 of the 10 CR maps from CR1601-1610 (in 1973 and early 1974) during the manned portions of the Skylab mission using the EUV He 304Å observations from Bohlin and Rubenstein (1975) and reproduced for CR1605 and CR1609 in Bohlin and Hulburt (1977).

In addition, we have scanned and will process into the McA the atlas of 132 Hα synoptic charts for SC 19 that was produced by Makarov and Sivaraman (1986). This will provide 5 full SCs of CR maps that are in the same consistent, machine-readable format for analyses of filaments and polarity boundaries. We note that no consistent CH boundary data are available before the Skylab period in 1973.

3. ANALYSIS HIGHLIGHTS

3.1. Solar Cycle Evolution of Open and Closed Magnetic Structures

A unique aspect of the McIntosh archive is its capability for simultaneously representing closed and open magnetic structures over a range of time scales. Figure 4 shows the global evolution of sunspots, plage and filaments for all of the McA data processed to date starting with CR 1513 in October 1966 and ending with CR 2086 in July 2009 in heliolatitude vs time. Sunspots and plage are plotted together in Figure 4a and show the classic butterfly diagram, with sunspots appearing after each solar minimum first at high latitudes, and emerging progressively closer to the equator as the cycle continues.

In Figure 4b the sunspots in orange and the location of the most poleward filament for each CR in green dots are plotted together. The polemost filaments indicate the “rush to the poles” which is a tracer of the solar magnetic polarity reversal process (e.g., Altrock, 1997). After this reversal, the old polar crown filament is replaced by a secondary crown filament in both hemispheres (McIntosh, 1992). This process has been traced back to SC 14 in 1904 using filament data from Meudon Observatory (Makarov and Sivaraman, 1983; Li et al., 2008) and from Meudon and Kislovodsk Observatories (Tlatov et al., 2016), and recently back to SC 15 in 1919 from newly processed KSO Hα data (Chatterjee et al, 2017). This behavior is also mimicked in green line coronal observations extending back to 1939 (Minarovjch et al., 1998).

Figure 5a is a plot of the maximum latitude per CR for PCFs from the original McIntosh maps, including the “secondary” PCF that appears at lower latitudes and replaces the “true” PCF after the solar field reverses. Pat McIntosh (McIntosh, 2003) produced this expanded plot by combining the “rush-to-the-poles” period of SC 22 (see Figure 2) with then new data from SC 23. Our version of this plot from the
newly processed, digitized McA is shown in Figure 5b, in the same coordinate system with the north and south polemost filaments superimposed with different symbols (note we do not show the secondary PCF in this plot). We can see that it is a good match to McIntosh’s older plot. Mazumder et al. (2018) are also using the McA data set to plot filament, PIL and CH parameters. They find that over SCs 21-23 filament and PIL lengths are well correlated with the sunspot cycle.

McIntosh (e.g., 2003) first noted that both the polar crown of filaments and sunspots begin around the same period early in a cycle around 40° latitude. Then they diverge with the PCF moving poleward and sunspots and active regions moving equatorward. He also plotted the secondary polar crown which also moves poleward separated by at least 15° from the primary crown. This suggests that two large cells of opposite polarity in each hemisphere move poleward, a complication for the Babcock-Leighton model that features transport of active region-sunspot flux. He noted that the poleward motions of these four polar crowns were very similar for SCs 21-23, suggesting evidence of deeper-seated dynamo activity. Finally we note that when the primary crown reaches the poles and disappears, the secondary crown stops its motion, around latitude 55°, before either remaining at that latitude or drifting slightly equatorward through the remainder of the cycle. During the rise of the next cycle it then begins its rush to the poles as the primary crown of that cycle.

Figure 6a is a plot of the locations of the poleward-most CH boundaries per CR for SC 23. Circles (diamonds) indicate the most northward (southward) extensions of CH boundaries for each CR. Red and blue colors indicate magnetic polarity. This illustrates the divergent behavior of what may be two populations of CHs: the polar CHs which migrate poleward and low-latitude CHs that follow the sunspot/plage butterfly pattern. In Figure 6b this same plot is overlaid on a plot of the zonal flows (torsional oscillations) of the near-surface magnetic field, covering the period from the beginning of the GONG observations in 1995 to the present (from Howe, 2016). This shows that the poleward and equatorward magnetic flows over SC 23 match CH locations very well. Analyses of small-scale magnetic features, such as EUV bright points, magnetic regions of influence, g-nodes, torsional oscillations with sunspots and CH centers, have recently been made (e.g., McIntosh et al., 2014; Bilenko and Tavastsherna, 2016; Fujiki et al., 2016). The activity bands of these features emerge around 55° north and south latitudes and take 18-19 years to reach the equator. Our maps show a pattern of polar and low-latitude CHs with opposite polarities separated by the PCFs, which tend to demark this important 55° latitude zone (as above). This process of polar CHs reforming as a consequence of the migration of lower-latitude UMRs and CHs poleward was described by Webb et al. (1984) and Harvey and Recely (2002).

Figure 7 combines the sunspot, filament and CH locations for the entire McA data processed to date, showing how the patterns discussed for SC 23 are repeated in earlier cycles. In addition, the plot illustrates how the positive and negative-polarity open fields (blue and red) surround the closed-field filaments (green) and sunspots (orange), on a global scale. For the period for which we have continuous processed CH data, from just before the maximum of SC 21 (1980) to the start of SC 24 (2009), this demonstrates well how the dual cells of opposite-polarity in the higher latitudes of each hemisphere track each other through each SC, and how consistent the offset is between the higher-latitude open and closed regions and the lower latitude closed regions (sunspots and plage). These large-scale rearrangements of the open flux in unipolar areas and the formation of the polar CHs in SC 23 and 24 have recently been studied by Golbeva and Mordvinov (2017). These large-scale motions are somehow tied to the internal fluid dynamics of the Sun, and must be accounted for in dynamo models.

Mazumder et al. (2018) have recently studied the time variation of CH areas calculated from the McA maps. They find that the total CH area on the Sun is dominated by high latitude (> 40° latitude) CHs during most of a SC. As is well known, the total CH area is anticorrelated with sunspot number, sharply dipping to a minimum at SC maximum. These minima were reached in 1990-1991 in SC 22 and 2001 in
SC 23. They also find a north-south asymmetry in the CH areas around these same times, which is indicative of a lag or temporal offset in the magnetic field development between hemispheres during these SCs (see next Section 3.2).

3.2. The Polar Field Reversal Process

Of particular interest with our currently available processed data is the evolution of the polar magnetic regions of the Sun and how the rush to the poles and other patterns occur during the period when the polar fields reverse near each SC maximum. Despite data gaps, we see in Figure 7 that there is data coverage during these epochs for three consecutive SCs; in the north these occur in SC 21 around CR 1700, SC 22 ~ CR 1830, and SC 23 ~ CR 1970. In the south the reversals lag those in the north, in agreement with the early dominance of magnetic flux and its reversal in the northern hemisphere during each of the last 4 SCs (e.g., Petrie 2015). This process in the south during SC 22 is obscured here because of the long data gap between the maximum of SC 22 and the start of SC 23. The polar field reversal process is evident on these data by two features: 1) the end of the filament rush to the poles, i.e., the polemost filament boundary decreases suddenly as the PCF disappears and the secondary crown is recorded as “polemost” (see Figure 5), and 2) the polar CH disappears before this and, sometime later, the polarity of the polemost CH reverses. This is revealed at the north pole as blue-to-red, red-to-blue and blue-to-red CH color changes during the three cycles, with the opposite pattern in the south.

Because the processed data set is in a consistent, machine-readable format, the maps can be displayed in various ways. One method that we find especially useful for displaying the polar reversal process is by displaying the data (which is in latitude-longitude coordinates for each Carrington rotation) mapped onto a sphere that can be viewed from different vantage points. This is illustrated for CR in Figure 8 which shows the north and south polar views for CROT 1728 plus two side-on views 180° apart centered on the equator. The online movies associated with Figure 8 (Movies 3-6) show the polar reversals and also the common occurrence of “swirling” patterns evident in the coronal holes/polar crown filaments. This type of pattern has been noted in coronal cavities (Karna et al., 2017) and in helioseismic ring-diagram analyses of near-surface flow anomalies (Bogart et al., 2015).

The polar magnetic field reversal process was first studied in some detail for SCs 20 and 21 by Webb et al. (1984). The goal was to use the then-newly understood CH boundary mapping to better constrain dynamo models. CH data were obtained from X-ray rocket and OSO-6 images and HAO K-coronameter white light maps for SC 20 and He-I 10830Å maps for SC 21. These data were combined with McIntosh’s original synoptic maps to determine the timing of five events around the maximum of each SC in each hemisphere: the sunspot number peak, the polarity reversal, the disappearance of the PCF, the first appearance of mid-latitude CHs of new-cycle polarity, and the earliest complete coverage of each pole by a hole. The time offsets, or lags between the reversal and the last three events was also determined. As discussed above, with the processed McA we can now extend this type of study over four consecutive SCs through SC 23.

3.3. Studies of Active Longitudes

As discussed in Sec. 1.3 time-series zonal “stack plots” of the synoptic maps are useful in tracking large-scale features, including polarity boundaries, CHs and active longitudes, over SC time scales. Active longitudes, where sunspots and magnetic flux emerge preferentially (e.g., de Toma et al., 2000), are easily tracked on stack plots (McIntosh, 2003). Evidence for the persistence of two active longitudes separated by 180° for 100 years has been found in historical records of sunspot locations (e.g., Berdyugina and Usoskin, 2003) and in recently-digitized white-light images from the Kodaikanal Observatory (Mandal et al., 2016).
Webs et al. (1978) used the McIntosh maps to link the evolution of CH boundaries with filament eruptions and coronal transients. The evolution of so-called “switchback” neutral lines, relatively sharp reversals in the direction of a PIL, are common features of large-scale PILs and may indicate stress buildup leading to increased solar activity and possibly eruptions (e.g., van Ballegooijen et al., 1998). Their evolution can easily be tracked on McA maps (e.g., McAllister et al., 1996).

Decadal stack plots have demonstrated the evolution of gaps in the polar crown, polarity reversals and longitudinal pattern drifts that circle the Sun over a cycle. McIntosh et al. (1991) is an atlas of stack plots of the Hα synoptic charts covering two full SCs, from 1966-1987. The long-term zonal stack plots show clearly the evolution of magnetic structures over narrow latitude bands. Latitude bands covering ~ 10 to tens of degrees in each hemisphere or centered at the equator are selected from each map, and plotted or “stacked” one above the other in time series. The time series are made adjustable from a few consecutive maps to maps covering a solar cycle or so in time. We shows in Figure 3a an original figure P. McIntosh produced to display the large-scale polarity patterns for high solar latitudes for 1964-1967. We have written code based on the McIntosh et al. (1991) work to produce similar stack plots from the digitized McA. The three sets in Figure 3b illustrate this stack-plotting, but for the entire colorized McA SC 23 (13 years) data in 40° zones for the northern, equatorial, and southern zones. These patterns are associated with, e.g., active longitudes of magnetic flux emergence (de Toma et al., 2000), recurring high-speed solar wind streams (Gibson et al., 2009), and periodic forcings of geospace and the upper atmosphere (Emery et al., 2009; 2011). The McA stack plots demonstrate clear periodicities in both closed (e.g., sunspot) and open (e.g., CHs) fields, magnetic polarity reversal during the SC, and differential rotation rates between the poleward and equatorial zones.

Figure 9 is a sequence of equatorial slices (-20° to +20° heliolatitude) stacked along a curving, snake-like axis advancing in time using the McA data for all of SC 23 (CRs 1910 – 2084) as in Figure 3. The width of the “snake” is the 360° heliolongitude for each CR (after, e.g., McIntosh and Wilson, 1985). The colors follow the key as in Figure 1 (bottom). Active longitudes are evident in quiet sun, sunspots, and coronal holes. A ~180° longitudinal asymmetry is particularly evident just after solar maximum; this is consistent with studies spanning ~100 years of sunspot active longitudes (e.g., Berdyugina and Usoskin, 2003).

3.4 Linking Large-Scale Patterns to the Solar Wind

The persistence of low-latitude coronal holes coupled with solar rotation drives periodic behavior, both in the solar wind and in the Earth's space environment and upper atmosphere, as has been studied extensively for the SC 23 declining period and the extended solar minimum that followed (see, e.g., Temmer et al., 2007; Gibson et al., 2009; Luhmann et al., 2009). This period included the Whole Heliosphere Intervals in 2008-2009 (e.g., Gibson et al., 2011; Thompson et al., 2011; Webb et al., 2011). This otherwise quiet time period, e.g., with few sunspots, was characterized by sustained longitudinal structure, first with three and then two near-equatorial open-field regions, as shown in the top part of Figure 3b, middle panel.

Figure 10 compares CR stackplots showing (left) in-ecliptic solar wind speeds, from NASA OMNI data, and (right) surface features from the McA during SC 23. The solar wind speeds versus Carrington longitude plot reveals the presence of high-speed streams that recur over multiple rotations and fade in and out over time (see also Lee et al., 2011). The occurrences of these streams line up well with the presence of large equatorial CHs as recorded in the McA maps (Cranmer et al., 2017; Gibson et al., 2017). The long-lived coronal holes (blue/red) in panel (b) rotate at a rate somewhat faster than the 27.275 day Carrington rotation, and thus have a positive slope in this plot. This correlates well with the slopes seen in the fast wind streams indicated in panel (a).
The patterns shown in Fig. 10 extend to the Earth’s space environment and upper atmosphere. Correlations are found between high-speed solar wind streams and modulations of the aurora and geomagnetic indices, radiation belts, ionosphere, and thermosphere (Gibson et al., 2009; Solomon et al., 2010; Lei et al., 2011). Long-time series analyses over years and decades show periodicities in all of these quantities that may be associated with periodicities in the fast solar wind, and consequently the distribution of open magnetic flux at the Sun in the form of CHs (Emery et al., 2011).

3.5. Studies of Differential Rotation

Figures 3b and 9 clearly show that the equatorial CHs between +/- 20° solar latitudes shift eastward with time, completing a full circle in about 180 maps, or 2.5 years. A Carrington rotation is 27.38 days relative to our observing position on the Earth (the sidereal rate), where the equatorial zone rotates faster than mid-latitudes or the poles. Thus, the observed eastward shift of low-latitude coronal holes embedded in polarity regions could simply represent the lower latitudes rotating at about 25 days, provided CHs are fixed with respect to the solar surface. However, the apparent rotation eastward is not as strong during the solar minimum periods at the top and bottom of the plots when there are fewer low-latitude CHs, which may indicate a differential rotation of the CHs that departs from solar surface flow rates.

Figures 3b shows for SC 23 the equatorial zone and the northern and southern polar zones. Near solar minimum (top and bottom of the plots) the polar zones show unipolar coronal holes at all latitudes, but at solar maximum and in the declining phase the slower polar rotation rate is evident. The CHs in the polar zones show a westward drift at solar maximum, which is much more pronounced in the northern hemisphere with both the blue positive polarities in 1996, and the red negative polarities in 2002 compared to the southern hemisphere. Again, this reflects a variation in differential rotation rates in the CH vs solar surface flows. It is of interest to see whether or how these interhemispheric differences appear in earlier solar cycles.

Studies of sunspot active-longitude differential rotation (e.g., Usofskin et al., 2005), Mandal et al., 2016) find a rotation rate of the active longitude location matching the surface flow at that latitude. This is in contrast to individual sunspots which generally rotate faster than the surface does, indicating they are rooted below the near-surface shear layer (Thompson et al., 2003). Studies of CH rotation indicate that polar CHs may rotate rigidly, while low-latitude CHs rotate more differentially but with a variability possibly associated with coronal-hole lifetime and solar-cycle phase (see, e.g., Ilkhanov and Ivanov, 1999). Such variability may contribute to the range in slopes of CH patterns seen in the figures.

4. CONCLUSION

4.1. Summary

We have demonstrated some examples of how the newly-processed McIntosh Archive (McA) maps can be used to investigate long-term solar variability over SC periods. Analyses of these data help in understanding the SC-variation of the toroidal and poloidal components of the magnetic field, its connection to the dynamo and dynamo models, the sources and evolution of active regions, CHs, filaments, and how the rotation rates of the various solar features vary over these cycles. Thus, the McA maps are enabling studies of the SC variation of both closed and open magnetic structures in a new way, and eventually will cover five contiguous SCs, 19-23.

4.2. Discussion
The unique power of the McIntosh archive is its capability to simultaneously represent closed and open magnetic structures over a range of time scales. The completion of the full McA digitization will provide the community with a comprehensive resource for addressing key questions including: How do active longitudes vary within and between solar cycles, for both closed and open magnetic features? Where are closed and open magnetic features rooted (as evidenced by rotation rate), and how does this depend on SC phase, feature lifetime, and latitude? How does the evolution of open and closed magnetic features relate to surface flows on SC time scales? Answering these questions has important implications for our understanding of the solar dynamo, and for our interpretation of periodic variations of Earth's space environment and upper atmosphere.

Over past decades the capabilities of dynamo-type models have increased to today’s fully 3-D MHD numerical simulations, with the goal of being able to reproduce the solar cycle in terms of surface manifestations such as sunspots and the other patterns evidenced in the McA maps (e.g., Charbonneau, 2010). However, we still lack sufficient knowledge of the solar interior, especially the deep convection zone. Recently, some research has focused on the SC-variation of small-scale magnetic features such as EUV bright points and their relation to torsional oscillations and “giant cells” as indicators of magnetic activity in the deeper-seated convection zone (e.g., McIntosh et al., 2014; 2018). The subsurface flow anomalies noted in Section 3.2 could be related to east or westward surface motions of extended convective structures “wound up” by differential rotation (e.g., Hathaway et al., 2013). Studies of the motions of such patterns compared to subsurface differential rotation profiles and other helioseismic data can address whether or not they are surface manifestations of deep convective cells (Bogart et al., 2015). Also, zonal flow anomalies at high latitudes could be related to the evolution of the torsional oscillation at high latitudes and, therefore, the evolution of the solar cycle (discussed in Section 3.1 and shown in Figure 6). The McA will be very useful for all these studies for understanding the surface features and transport processes in the context of new models and simulations.

The McA can also be a very useful tool for improving our understanding of and ability to predict solar activity and space weather. Such predictions are needed to protect assets vital to our national security and the operations of technologies used worldwide in civilian daily life. Analyses of this accurate baseline of solar activity that covers ~ 45 years (four consecutive SCs) can enhance our understanding of solar activity and our capability to predict it. In addition, improving public access to historic measurements of CHs and filaments is helping researchers to better understand and study the connection between these phenomena at the Sun and their effects at Earth (e.g., Knipp et al., 2016).

4.2 Future Work

When the McA is completed, we plan to analyze the full data set and publish the results. Some of the topics we are working on include: 1) analysis of the rush to the poles phenomenon involving the PCFs, CHs, and unipolar regions; 2) extending the results of the Webb et al. (1984) study on the polar field reversal process through SC 23; 3) analysis of the differential rotation differences using time-variation analyses programs as a function of solar latitude, solar cycle, and hemisphere; 4) studies of active longitudes and switchback PILs as related to solar activity, eruptions and space weather; 5) analysis of linkages between large-scale solar surface patterns and solar wind streams and the terrestrial environment.

Acknowledgements

We dedicate this project to Patrick McIntosh who passed away in October 2016. We are grateful to his daughter, Beth Schmidt for granting us permission to use his original data. Pat should be considered one of the founding Fathers of what we now call Space Weather, because of his pioneering work in forecasting research starting at the Space Environment Laboratory at the National Oceanic and
Atmospheric Administration (NOAA) in Boulder. The work of the authors was supported by NSF RAPID grant 1540544 and NSF grant 1722727. The National Center for Atmospheric Research (NCAR) is supported by the National Science Foundation. The repository for the data discussed here is available at: https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-imagery/composites/synoptic-maps/mcintosh/, and at: https://www2.hao.ucar.edu/mcintosh-archive/four-cycles-solar-synoptic-maps.

REFERENCES


**Figure Captions**

Figure 1. *(Top)* Scanned image (Level0) of an original synoptic map in from March 2002 created by Pat McIntosh. *(Bottom)* Processed colorized map (Level3) from the new McIntosh archive with negative (grey) and positive (white) polarity magnetic fields, negative (red) and positive (blue) CHs, filaments (green), and PILs (black). The Supplementary Material contains movies of the full McA of the original synoptic maps (Level1; Movie 1) and of the final processed maps (Level3; Movie 2).

Figure 2. Maximum, poleward-most latitudes of filaments in the primary and secondary PCFs for both hemispheres for cycles 20–22. Both hemispheres have been folded together. For each cycle, the polar-most (primary) crown begins the “rush to the poles” in both hemispheres at about ∼55° latitude. The replacement polar crown begins moving poleward at about the same time from ∼40° latitude. P. McIntosh produced this figure in 1998; also see Figure 4 in Webb (1998) and Figure 5 in McIntosh (2003).

Figure 3. *(Left)* Figure by P. McIntosh displaying the large-scale polarity patterns for high solar latitudes for 1964-1967 comparing north and south poleward zones for each 360° CR. The barber-pole patterns denote the varying rotation rates of the patterns. *(Right)* The same stack-plotting, but for the entire McA SC 23 (13 years) data in 40° zones: North polar zone = N30°-N70°, Equatorial zone = S20°-N20°, South polar zone = S30°-S70°. These show how the polarities reverse during the SC and the difference in rotation rates between the poleward and equatorial zones.

Figure 4. Butterfly-type plots of all of the McA data processed to date starting with CR 1513 in October 1966 and ending with CR 2086 in July 2009. The Year scale is at the top and the CR scale at the bottom. *(a)* McA plot of sunspots (orange) and plage (yellow), both associated with ARs and revealing the classic butterfly pattern. *(b)* Plot of the McA sunspots (orange) and the poleward-most filament boundaries per CR (green) for this period. The same “rush to the poles” as shown in Figure 2 during the rise phases of both SC 22 and 23 is evident as well as the appearance of the new PCF after each maximum.

Figure 5. *(Top)* Plot of the maximum latitude per CR for PCFs from original McIntosh maps, including the “secondary” PCF that appears at lower latitudes and replaces the “true” PCF after the solar field reverses. Like the SC 20-22 plot in Figure 2, P. McIntosh produced this expanded plot in 2003 (Figure 6 in McIntosh, 2003) comparing the “rush-to-the-poles” periods of SC 22 and 23. *(Bottom)* The current version of this plot for the McA that has been completed to date for SCs 22 and 23. This plots only the single polemost filament location from each CR map, and so does not separate the true and secondary PCF branches as top plot does. For each SC the northern hemisphere locations are plotted as filled green circles and the southern as filled blue diamonds.

Figure 6. *(Left)* The poleward-most CH boundaries per CR for SC 23. Circles (diamonds) indicate the most northward (southward) extensions of CH boundaries for each CR. Red and blue indicate magnetic polarity. *(Right)* This same plot overlaid on a plot of the zonal flows (torsional oscillations) of the near-surface (0.99 Rs) magnetic field from GONG, MDI, and HMI data, covering the period from the beginning of the GONG observations in 1995 to the present (from Howe, 2016; prepared by R. Komm). This shows that the poleward and equatorward magnetic flows over SC 23 match CH locations very well.

Figure 7. Butterfly-type plots of all of the McA data processed to date starting with CR 1513 in October 1966 and ending with CR 2086 in July 2009. The Year scale is at the top and the CR scale at the bottom. This plots for each CR all sunspots (orange), the poleward-most filament boundaries (green), and the poleward-most CH boundaries (red and blue). As in Figure 6a, circles (diamonds) indicate the most
northward (southward) extensions of CH boundaries for each CR, and red and blue indicate magnetic polarity.

Figure 8. An example of the transformation of the Mercator-type rectangular McA synoptic maps into a spherical coordinate system. In this coordinate system, the data for each CR appears on a rotating sphere and can be viewed from different vantage points. This is illustrated for one CR (1728) showing the two side-on views 180° apart centered on the equator and at (a) 45° and (b) 225° Carrington longitudes plus (c) north and (d) south polar views, respectively. Movies 3-6 of these same four views for the final, Level3 McA data set are provided in the Supplemental Material.

Figure 9. A sequence of equatorial slices (-20° to +20° latitude) is stacked along a curving axis, like a snake, advancing in time through CRs 1910-2084 (SC 23); width is longitude (after, e.g., McIntosh and Wilson, 1985). Colors are as in Figure 1 (bottom). The panels on the right show how an equatorial latitude strip from one CR is patched into a stackplot which in turn becomes a curvilinear part of the entire “snake” that traverses all of SC 23.

Figure 10. CR stackplots showing (left) in-ecliptic OMNI wind speeds and (right) surface features from the McA, both for the duration of SC 23. In the left panel, white denotes v ≤ 450 k m s⁻¹ and increasingly darker shades of purple eventually saturate at the darkest color for v ≥ 750 k m s⁻¹. Longitudes have been offset by 50.55°, or 3.83 days, to account for propagation from the Sun to 1 AU at a mean speed of 450 k m s⁻¹. The right panel shows equatorial (+20° from equator) features, with blue [red] showing coronal holes of positive [negative] polarity, cyan [gray] showing quiet regions with predominantly positive [negative] polarity, orange indicating sunspots, and green indicating filaments. From Cranmer et al. (2017).

Supplementary Material

Movies:
1 - Original (L1)
2 - Final processed CR maps (L3) (add blanks to show where gaps are)
3 - Spherical coordinates movie of Solar North pole
4 - Spherical coordinates movie of Solar South pole
5 - Spherical coordinates movie centered on Heliolongitude of 45°
6 - Spherical coordinates movie centered on Heliolongitude of 225°

Other:
1 – McA metadata spreadsheet